# Water Use by Windbreak Trees in the Sahel

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# Abstract

Windbreaks have been promoted as a means of arresting degradation of agricultural lands in the Sahel resulting from deforestation, but competition for water between windbreak trees and adjacent crops must be minimised if windbreaks are to be successfully established in areas where crop production is threatened by loss of trees. Research was done, consequently, between 1991 and 1993 in southern Niger, in West Africa, to aid development of strategies for the deployment of windbreaks in the Sahel which minimise competition for water. The objectives of this research were to: (1) quantify water use by windbreak trees; (2) determine the source of water utilised by windbreaks; and (3) identify the environmental and physiological variables controlling transpiration by windbreak trees.

The heat-pulse method method was used to measure water use during the cropping season by three tree species growing in windbreaks and patterns of water extraction from soil adjacent to windbreaks of each species were assessed from soil moisture contents measured by neutron attenuation. *Azadirachta indica* transpired less water than either *Acacia holosericea* or *Acacia nilotica* and extracted less water from the rooting zone of nearby crops, and was thus shown to be the least competitive of these tree species.

Naturally-occurring variations in the ratio of the stable isotopes of oxygen ($^{18}O/^{16}O$) in water were utilised to trace the sources of water transpired by *Azadirachta indica* trees in windbreaks and adjacent crops of pearl millet (*Pennisetum glaucum*) at two locations with contrasting water table levels. Where groundwater could be accessed by the trees, they obtained large proportions of their water from surface layers of the soil only when water there was plentiful, for example after rain. Where groundwater was not accessible, the trees fulfilled their requirements for water from the surface layers of the soil profile throughout the year. Thus, competition for water between windbreaks and crops is more severe at locations where trees cannot utilise groundwater.

Energy budgets of windbreaks of *Azadirachta indica* trees were measured during four periods of the year. Net radiation absorption by windbreak canopies was measured using an array of linear net radiometers, while the heat-pulse technique was used to determine latent heat fluxes. Sensible heat fluxes were calculated from measurements of foliage temperatures and aerodynamic conductances estimated from *in situ* measurements of leaf boundary layer conductances, made using heated leaf-replica pairs, and the conductance for transfer between the outer limits of the leaf boundary layers and the bulk air surrounding the trees. The latter conductance was estimated by comparing leaf boundary layer conductances with bulk aerodynamic conductances for whole trees, which were determined from the rate of evaporation from artificially-wetted, excised trees. During the rainy season, up to 60 % of latent heat fluxes from the windbreaks resulted from enhancement of transpiration by advection and vertical entrainment of dry air, but advection and entrainment depressed transpiration to as little as 40 % of the equilibrium rate during the dry season. Thus, unlike sheltered crops, water use by windbreak trees is largely driven by the imposition of the ambient vapour pressure deficit at leaf surfaces.

Physiological control of transpiration by windbreaks was assessed by calculating values of the decoupling coefficient, $\Omega$, from the aerodynamic and surface conductances of the canopies of windbreaks of *Azadirachta indica* trees. Values of $\Omega$ were found to be $\approx 0.3$ at moderate wind speeds in all except the dry season, when $\Omega$ was $\approx 0.1$. Windbreak trees consequently have very good physiological control over transpiration and so are able to moderate their use of water by stomatal adjustment when the availability of water from the soil becomes limited.

Management strategies which reduce water use by windbreak trees must be used at locations where lack of accessible groundwater is likely to result in severe competition for water between trees and crops. At these locations, land-use planners should select tree species with low surface conductances and root systems that do not spread laterally for large distances and they should advise that windbreaks are pruned at critical times of year. Models of water use in windbreak systems should be developed in the future to help planners prescribe management regimes for specific locations.

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This thesis records the results of four years of endeavour amidst the splendour of Edinburgh and the exotic ferment of Sahelian Niger and, while it is my hope that the scientific achievements documented here can contribute in some small way to improving the lives of the people of the Sahel and to enhancing their stewardship of their environment, it is inevitable that the time I have spent working on this thesis has left a greater mark on me personally than I have left in either Edinburgh or Niger. Throughout this period, the scientific excellence and the standard of scholarship demonstrated by those around me has taught me much about the process of scientific enquiry and has served as an example that I have tried my best to emulate and that will remain with me for many years to come. Equally, the indefatigable spirit of the people of Niger will always serve as a humbling example to me of the value of tenaciousness and determination in any human endeavour and the privilege of working and living in their country has shown me that the challenges of bridging the gaps between disparate cultures are far more rewarding than they are difficult.

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# Chapter 1

## Introduction: Windbreaks, Water and Agriculture in the Sahel

### 1.1 Agriculture in the Sahel

The Sahel is a semi-arid region in northern Africa, stretching across the continent from Ethiopia to Senegal in a 400-600 km-wide band between the Sahara desert to the north and the Sudanian zone to the south. The annual northward migration of the inter-tropical convergence zone brings rainfall to the Sahel in a single annual rainy season and mean annual rainfall varies between 100 mm at the northern extreme and 600 mm at the southern extreme of the region (Le Houérou, 1989). Inter-annual variability in rainfall is high, however, with positive or negative deviations in annual rainfall often persistent for a number of years (Nicholson, 1980; Agnew and Anderson, 1992; Sivakumar *et al.*, 1993). Periodic droughts are consequently a prominent feature of the Sahelian climate, creating instability in agricultural production in the region (Olsson, 1993; Sivakumar *et al.*, 1993).

Sedentary farmers and nomadic pastoralists co-exist in the Sahel, with farmers dominant in southern areas where mean annual rainfall is more than 400 mm and nomads inhabiting northern areas where the climate is too arid for secure crop production (Agnew and Anderson, 1992; Sivakumar *et al.*, 1993). Farmers in the south normally employ a mixed farming system, both growing crops and raising livestock (Agnew and Anderson, 1992). The staple cereal crops in the Sahel are pearl millet (*Pennisetum glaucum* (L.) R. Br.) and sorghum (*Sorghum bicolor* (L.) Moench), although these are often intercropped together and with leguminous crops such as cowpea (*Vigna unguiculata* (L.) Walp.) and groundnut (*Arachis hypogaea* L.) (van den Beldt, 1990; Ramaswamy and Sanders, 1992). Traditionally, cropping of fields has been rotated with fallow periods in which successional shrubs and grasses are allowed to grow for periods of several years in order to restore soil fertility lost during cropping over periods of similar length (Broekhuyse and Allen, 1988; Rowland, 1993).

#### **1.1.1** *Constraints on Sahelian agriculture*

Crop production is severely constrained by several features of the Sahelian environment. Shortages of water caused by erratic rainfall can limit crop growth in some years and at some locations and even cause crop failure when rainfall in a season is very low or very poorly distributed (Agnew and Anderson, 1992; Zaongo *et al.*, 1994). Prolonged dry spells during the rainy season can be very damaging to crop productivity because most arable lands in the region have sandy soils with very low water-holding capacities, so that the ability of crops to survive on stored soil moisture is limited. Fertility of these soils also constrains crop production because the availability of nutrients such as nitrogen and phosphorus is often low and soils are commonly acidic, so that aluminium and manganese toxicity can stunt crop growth (Zaongo *et al.*, 1994). Soils in the Sahel tend to be very variable over short distances and so fields commonly contain patches where fertility limits crop growth alongside other areas where the availability of moisture is limiting (Brouwer *et al.*, 1993). Most farmers cannot afford costly inputs that could be used to alleviate constraints on crop yields, such as chemical fertilizers, liming and irrigation, and so management of nutrient cycling and soil water in farming systems in the Sahel needs to be as efficient as possible (Sivakumar and Wallace, 1991; Powell and Williams, 1993).

Constraints on crop production in the Sahel have been exacerbated in recent decades by environmental degradation brought about by drought and population growth. Annual rainfall has been declining in the region since the 1960s, displacing rainfall isohyets 100-150 km southwards (Sivakumar, 1992), and severe droughts occurred in the early 1970s and early 1980s. Concurrently, population growth rates in Sahelian countries have been amongst the highest in the world (U.S. Bureau of the Census, 1991), so that while the severity of constraints on crop production has worsened, demand for food, wood and other products from the land has increased. This has forced farmers to expand agricultural production onto communal grazing lands and marginal lands with poor soils and to reduce and even eliminate the fallow period used to replenish soil fertility (Broekhuyse and Allen, 1988; Ramaswamy and Sanders, 1992; Powell and Williams, 1993). Crop yields have consequently fallen by a third to a half of the yields achieved with adequate fallowing (Ramaswamy and Sanders, 1992). Furthermore, tree cover has been lost because trees have been killed by drought and cut as a result of the reduction in the supply of wood from fallow areas and the increasing demand for wood for fuel and construction by the growing population. In combination with overgrazing of pastures, this has exposed already fragile soils to erosion by water and wind (Ramaswamy and Sanders, 1992; Michels *et al.*, 1993) and so excarbated constraints on agriculture and reduced the security of food supplies for people living in the Sahel.

## 1.2 Agroforestry in the Sahel

Trees and shrubs play an important role in both the farming systems and natural ecology of the Sahel. Perennial woody plants provide fodder for animals during the long Sahelian dry season and they protect soils from wind erosion caused by the harmattan winds of the dry season and, in the period before annual plants and crops are established, by the strong winds which often precede rainstorms (Michels *et al.*, 1993). People in rural areas of the Sahel generally rely on wood for fuel and as a construction material and there is also demand for other products from trees such as fruit, seeds and leaves for consumption by livestock or as human food (van den Beldt, 1990). As environmental degradation in recent decades has exacerbated contraints on crop production, agroforestry systems have been recognised as systems of land resource management that can both meet demands by local people for tree products and improve the sustainability of crop production.

### **1.2.1** *Characteristics of agroforestry systems*

Agroforestry is the term used to describe land-use systems in which woody perennials are grown on the same area of land as crops and/or animals, either in some form of spatial arrangement or a time sequence, so that there are economic and ecological benefits from interactions between woody and non-woody components of the system (van den Beldt, 1990; Weischet and Caviedes, 1993). There are many different agroforestry systems in use around the world, in both temperate and tropical regions, the characteristics of each determined by ecological, cultural and socio-economic requirements at each location (Nair, 1989, 1991). In systems combining trees and crops, economic benefits from agroforestry arise from the use of multipurpose tree species that contribute several desired products to total production from an area of land (von Maydell, 1990; Verinumbe, 1991) and from enhanced crop yields that can result from positive ecological interactions between tree and crop growth (Anderson and Sinclair, 1993). Improved crop yields and, additionally, increases in the long-term sustainability of crop production can occur when trees are integrated into crop production because of better soil fertility (Young, 1989; Szott et al., 1991; Weischet and Caviedes 1993), complementary use of resources by trees and crops (Anderson and Sinclair, 1993; Ong and Black, 1994), more favourable crop microclimate (Rosenberg, 1966; Ogbuehi and Brandle, 1981; Stigter *et al.*, 1993; Brenner *et al.*, 1995b) and reduced soil erosion (Young, 1989; Michels, 1994). As a consequence of the positive effects of interactions between trees and crops, it is possible for total yields of plant products to be higher where land is managed using agroforestry than where conventional agriculture or silviculture is used (Anderson and Sinclair, 1993).

Interactions between trees and crops in agroforestry systems can also, however, have negative effects. Trees can harbour insect pests and crop pathogens, allelopathic interactions between species are possible and trees and crops growing together can compete for limiting resources, so that growth of one or both is reduced (Ong *et al.*, 1991; Anderson and Sinclair, 1993). Above-ground competition occurs when trees shade adjacent crops and below-ground competition occurs when uptake of water or nutrients by roots of one species causes drought stress or nutrient deficiencies in neighbouring species (Ong *et al.*, 1991; Anderson and Sinclair, 1993; Campbell *et al.*, 1994). Where negative effects outweigh the positive influences of combining trees and crops, farmers are unlikely to adopt agroforestry as a system of land-use management, so that the potential benefits of agroforestry for soil conservation and the long-term sustainability of agriculture are lost. Thus, research into the processes controlling interactions between trees and crops is required in order to enable farmers and agronomists to develop effective management strategies for agroforestry, so that the benefits of agroforestry can be fully realised.

### **1.2.2** *Windbreaks in the Sahel*

Two systems of agroforestry are prominent in the Sahel. The first, the parkland system, is widely encountered in semi-arid regions of sub-Saharan Africa and the second, in which lines of trees are planted in windbreaks, is less common (van den Beldt, 1990). In the parkland system, mature trees of many species are dispersed in cropped fields and yields of crops beneath the trees are frequently observed to be enhanced, particularly beneath trees of *Faidherbia albida* (Del.) A. Chev., which competes only minimally with crops because it loses its leaves during the rainy season (van den Beldt, 1990; van den Beldt and Williams, 1992). Windbreaks are most frequently used in locations where the parkland system has become degraded by deforestation (Rocheleau *et al.*, 1988; van den Beldt, 1990), leaving soils subject to wind erosion and crop seedlings vulnerable to burial by moving soil (Michels *et al.*, 1993). Thus, planting windbreaks perpendicular to prevailing winds is an effective way of re-establishing tree cover on degraded lands and arresting further degradation by controlling soil loss.

Experience has shown that the microclimate in the lee of windbreaks promotes improved crop growth at many locations. Wind speeds in the lee of windbreaks are reduced in a "quiet zone" that often extends into the crop up to a distance of eight times the height of the windbreak (McNaughton, 1988; Brenner, 1991). The minimum wind speed in this zone, which can be as low as 30 % of the incident wind speed (van den Beldt, 1990), is usually found at lateral distances of between three and six times the height of the trees (van den Beldt, 1990; Brenner, 1991; Brenner *et al.*, 1995a), depending on the porosity of the windbreak and the stability of the atmosphere (McNaughton, 1988; Brenner, 1991; Brenner *et al.*, 1995a). Turbulent transport is reduced in the quiet zone, creating a warmer, more humid microclimate (Brown and Rosenberg, 1972; Skidmore *et al.*, 1972; Miller *et al.*, 1973; Rosenberg *et al.*, 1983) in which crop growth and yield are often enhanced (Ogbuehi and Brandle, 1981; Rosenberg *et al.*, 1983) and the influence of advection on evapotranspiration reduced (McNaughton, 1983).

In the Sahel, experience of the influence of windbreaks on crop yields is mixed. Ujah and Adeoye (1984), working in northern Nigeria with 10 m-high windbreaks of *Eucalyptus camaldulensis* Dehn., found that yields of pearl millet were up to 21 % higher in shelter than in an open field, although the magnitude of the yield increase varied with distance from the trees. In the Majjia Valley in central Niger, a network of windbreaks protecting over 3000 ha of cropland (DANIDA, 1991) has been established following severe deforestation (Harrison, 1987). There, Long (1989) and others (see van den Beldt, 1990) found that grain yields of millet were 20-25 % higher in fields sheltered by windbreaks of *Azadirachta indica* A. Juss. than in unsheltered fields, even when land occupied by the trees was accounted for. In contrast, Brenner *et al.* (1993) showed that, at a location in south-western Niger, grain yields of millet were enhanced at some distances behind windbreaks of *A. indica* but reduced at others, so that grain production per unit land area was unchanged in comparison to unsheltered fields.

Positive influences of shelter on crop yields in the Sahel have been attributed to larger crop leaf area and more efficient conversion of solar radiation to dry matter in sheltered fields as a result of higher air temperatures and lower water vapour pressure deficits (Brenner, 1991; Brenner *et al.*, 1995b). The benefits of shelter on crop yields in the Sahel can be negated, however, by competition between windbreaks and crops (Kessler and Breman, 1991). Brenner (1991) found that both shading of the crop by *A. indica* trees and below-ground competition reduced yields, but only as far as a lateral distance of approximately twice the height of the trees. Onyewotu *et al.* (1994) found much larger yield reductions adjacent to windbreaks of *E. camaldulensis* in northern Nigeria that were shown to result from competition between the trees and crop for water. Thus, it is possible that the variability observed in the Sahel in the response of crop yields to shelter by windbreaks is caused by differences both among locations and among tree species in the severity of competition between windbreaks and crops.

## 1.3 Water use by windbreak trees

The erratic nature of rainfall in the Sahel and the low water-holding capacities of most Sahelian soils are serious constraints on agricultural development in the region. Consequently, if windbreak systems are to be used successfully to arrest degradation of agricultural lands in the Sahel resulting from deforestation, it is vital that uptake of water by windbreak trees does not exacerbate limitations on crop productivity caused by lack of water. If crop yields are substantially diminished because water use by windbreak trees frequently causes adjacent crops to suffer moisture stress, the establishment of windbreaks is unlikely to be accepted by local farmers, despite the benefits their use may bring. Thus, competition for water between windbreak trees and crops must be minimised if windbreaks are to be adopted in areas where they are needed for soil conservation and the provision of tree products. The development of management strategies which minimise competition for water between trees and crops in windbreak systems would, consequently, contribute strongly to future efforts to enhance the sustainability of Sahelian agriculture by helping to make the establishment of windbreaks more attractive to local people.

Strategies to reduce competition for water between trees and crops in windbreak systems will be most useful if they are applicable under a wide range of environmental conditions. Such strategies are most likely to be developed on the basis of results from research into competition in agroforestry systems that focusses on the mechanisms controlling the utilisation of resources by component species in the systems (Monteith *et al.*, 1991; Anderson and Sinclair, 1993). Research into competition for water in windbreak systems should thus concentrate on the processes which control uptake of water by sheltered crops and windbreak trees. Brenner (1991) demonstrated that, in the Sahel, the modifications to crop microclimate induced by windbreaks cause crop transpiration to increase. However, much less is known about water use by windbreak trees. A programme of research was devised, therefore, in order to advance understanding of water use by trees in windbreaks sufficiently to enable development of strategies for the deployment of windbreaks in the Sahel which minimise problems resulting from competition for water. The objectives of this research were to: (1) quantify water use by windbreak trees; (2) determine where windbreaks extract water from; and (3) identify which environmental and physiological variables control transpiration by trees in windbreaks.

## 1.4 Specific objectives

Competition is likely to be strongest where demand for water by windbreak trees is high and where both trees and crops rely on water from the same source. Demand for water by windbreaks may depend on differences among tree species, on physiological properties of the trees and on atmospheric conditions, while the source of water taken up by windbreak trees depends on the availability of water from different sources. As summarised in Fig. 1.1, experiments were designed, consequently, to investigate differences among tree species in the quantity of water transpired, control of transpiration by trees in windbreaks and the influence of the availability of water from outside the rooting zone of the crop on extraction of soil water by windbreak trees. The specific objectives of the project are described below.

### **1.4.1** *Differences in water use among tree species*

Where competition between trees and crops occurs, it will be more severe from tree species which demand large amounts of water. Water use was measured, therefore, in several tree species growing in windbreaks in order to quantify transpiration and determine whether there are physiological differences among species which might be used for selecting species on the basis of relative water use (Chapter 2). The technique used to measure transpiration was validated in each species using laboratory and field methods (Appendix A).

### **1.4.2** *Sources of water for transpiration*

The potential competitiveness of tree species growing in windbreaks depends also on the distance to which lateral roots extend into the crop and extract water. Soil water profiles from the vicinity of windbreaks of several species were therefore

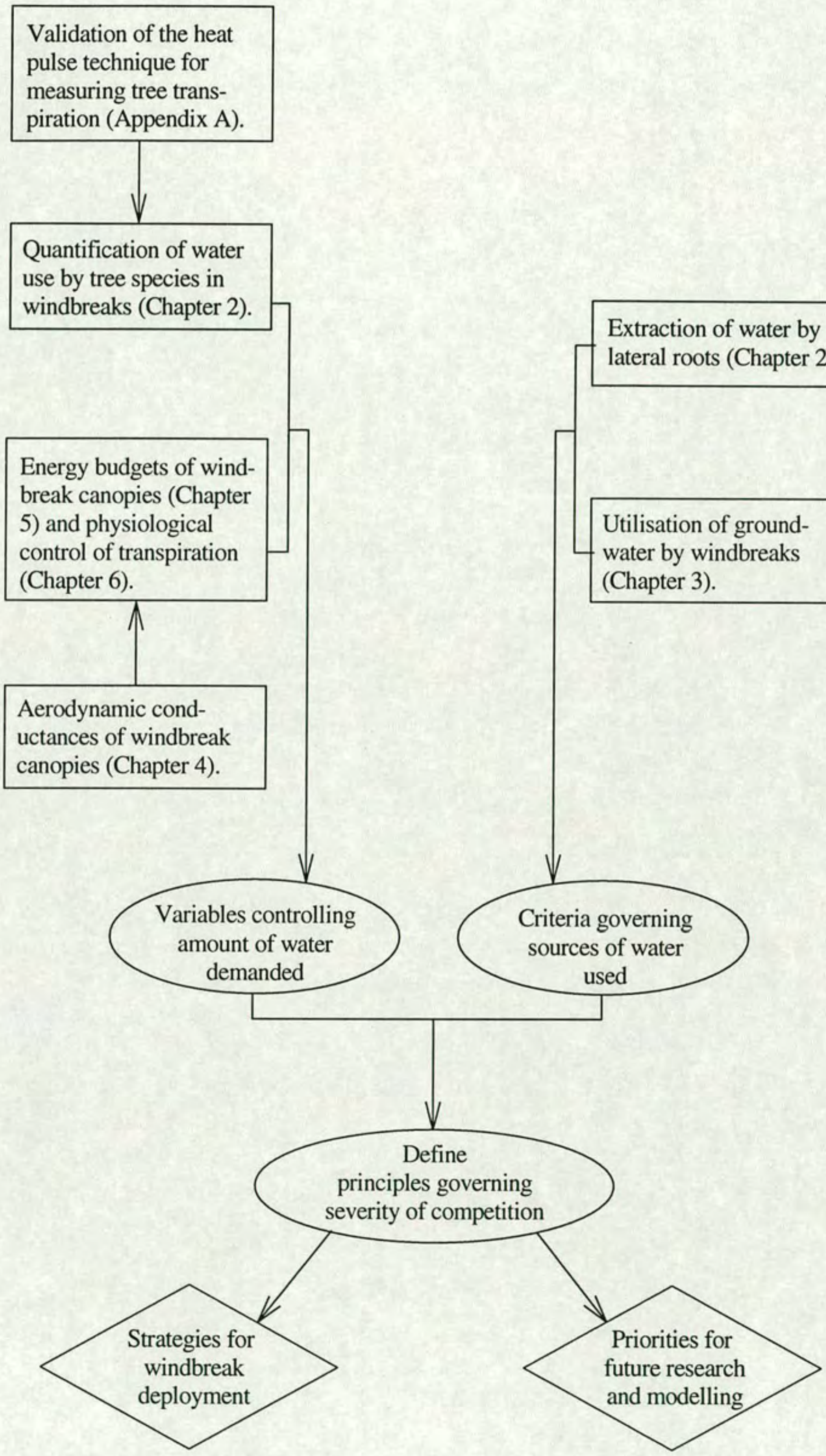

**Figure 1.1:** Diagram summarising the objectives of the research on water use by windbreaks in the Sahel undertaken between 1991 and 1993 in Niger, West Africa. Measurements are enclosed in rectangles, results and conclusions from experiments in ellipses and recommendations in diamonds.

examined in order to identify species with root systems capable of obtaining water from surface layers of the soil in the cropped area of the field (Chapter 2).

Annual crops have root systems that do not penetrate to great depths and so they depend on rainwater stored in the top 1 to 2 m of the soil profile. Windbreak trees, by contrast, are perennials with well-established root systems that can utilise water from much greater depths if it can be found there. Where such an alternative source of water is accessible to trees, there may be little competition for water between trees and crops, so that crop productivity is more likely to benefit fully from shelter. The sources of water used by trees and crops at two locations were therefore compared, using naturally-abundant stable isotopes in water to trace sources of transpired water, in order to determine whether the accessibility of groundwater to trees influences the severity of competition between windbreaks and crops (Chapter 3).

### **1.4.3** *Above-ground control of windbreak transpiration*

Transpiration by windbreaks depends on the amount of radiation absorbed by the foliage of the trees, the evaporative demand of the atmosphere and the degree to which windbreak trees are able to regulate water loss from their leaves. Energy budgets of windbreak canopies were consequently measured to determine how radiant energy is partitioned into latent and sensible heat fluxes in windbreaks (Chapter 5). For these measurements, a method of estimating aerodynamic conductances of windbreak canopies was first developed (Chapter 4) to enable calculation of sensible heat fluxes. The degree of physiological control exerted by windbreak trees over transpiration was then assessed by examining the magnitudes of the aerodynamic and surface conductances of windbreak canopies (Chapter 6). Thus, the environmental and physiological variables controlling water use by windbreak trees were determined. Strategies for managing the amount of water used by windbreak trees will be most effective if they are designed to influence these variables.

### **1.4.4** *Strategies for windbreak deployment and modelling of competition*

As indicated in Fig. 1.1, the results from these studies have been assembled and used to define principles governing the demand for water by windbreak trees and criteria for determining whether this demand can be met with minimal competition occurring between trees and crops. Strategies for deploying windbreaks in the Sahel were devised on the basis of these principles and it is recomended that land-use planners use these management strategies to help ensure that returns on the labour and money invested in the

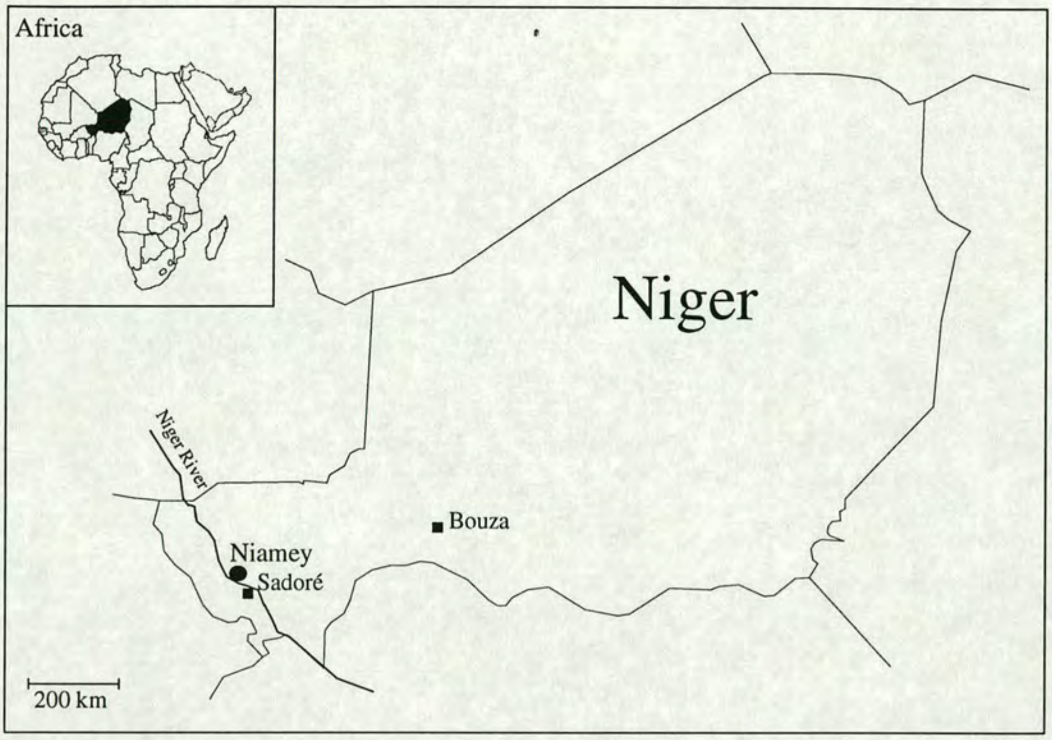

**Figure 1.2:** Map of the Republic of Niger, West Africa, showing the locations of the research sites at Sadoré and Bouza.

establishment of windbreaks are as high as possible. The results have also been used to develop priorities for further research and guidelines for researchers developing process-based models of competition in windbreak systems in the Sahel.

### 1.5 Research sites

This research programme was completed between 1991 and 1993 in southern Niger, in West Africa. The bulk of the research was done at the ICRISAT[1] Sahelian Centre at Sadoré (13°14'N, 2°16'E), approximately 45 km south of the city of Niamey, the capital of Niger, although some studies were also made in the Majjia Valley, near the town of Bouza (14°25'N, 6°03'E) in south-central Niger, some 400 km to the north-east of Sadoré (Fig. 1.2). The climate at both locations is typical of the Sahel, as shown in Fig. 1.3 for Niamey. The rainy season normally lasts from June to September, with mean annual rainfall of 545 mm at Niamey and 379 mm at Bouza (Sivakumar *et al.*, 1993). The remainder of the year is dry and temperatures can be very high (Fig. 1.3). The

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[1] International Crops Research Institute for the Semi-Arid Tropics

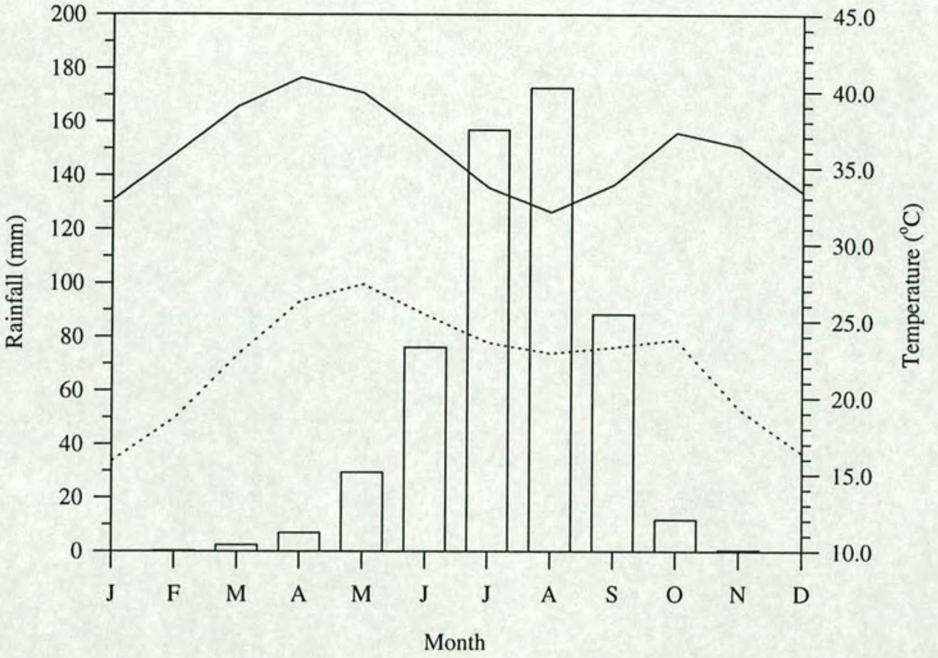

**Figure 1.3:** Summary of the climate at Niamey, Niger, showing monthly mean rainfall (bars) and monthly mean maximum (———) and minimum (·········) temperatures. [Source: Sivakumar *et al.* (1993)].

soil at Sadoré is a sandy alfisol (Psammentic Paleustalf) which overlies a hard layer of laterite (West *et al.*, 1984) and the soil at the Majjia Valley site is a loamy inceptisol (Fluventic Ustropept), without a lateritic layer (Long, 1989).

# Chapter 2

# Competitiveness for Water of Windbreak Trees in the Sahel

## 2.1 Introduction

Schemes for land-use management employing agroforestry have many positive influences on the productivity and sustainability of farming systems. Many different systems of managing trees and crops together exist around the world in both temperate and tropical zones (Nair, 1991) and increases in the long-term productivity of agricultural lands can arise from their use because of one or more of: (i) improved soil fertility because of nitrogen fixation by leguminous trees, capture and cycling of nutrients by deep-rooted trees and higher soil organic matter contents resulting from litter production by trees (Ong *et al.*, 1991; Szott *et al.*, 1991; Verinumbe, 1991; Anderson and Sinclair, 1993); (ii) amelioration of the microclimate for crop growth in fields sheltered by trees (Rosenberg, 1966; Ogbuehi and Brandle, 1981; Stigter *et al.*, 1993; Brenner *et al.*, 1995b); (iii) more efficient utilisation of resources for plant growth because of complementarity between trees and crops (Monteith *et al.*, 1991; Ong *et al.*, 1991; Anderson and Sinclair, 1993; Ong and Black, 1994); and (iv) reduced erosion of soils by wind and water because of reduced runoff (Young, 1989; Anderson and Sinclair, 1993) and lower wind speeds at the soil surface (Onyewotu, 1983; Michels, 1994). In addition to these biological benefits of tree-crop interactions in agroforestry, there are economic benefits to farmers and local people from products harvested from the trees. These products can be of particular importance in less-developed countries where resources for economic development may be scarce and include fodder for animals, wood for fuel and construction and fruit, seeds and leaves for human consumption (van den Beldt, 1990).

The potential benefits of agroforestry can, however, be outweighed by reductions in crop productivity that can render the incorporation of trees in systems for crop management unacceptable to farmers on an economic basis. Growth and yields of crops can be diminished by the presence of trees if the trees harbour crop pests or if there are allelopathic or competitive interactions between the trees and crop (Ong *et al.*, 1991; Anderson and Sinclair, 1993). The economic viability of appropriate agroforestry systems can be improved, therefore, if efforts are made to lessen the negative impacts of trees on crop productivity, but management strategies designed to do so must be developed on the basis of a sound understanding of the mechanisms of interactions between trees and crops if they are to be widely applicable (Monteith *et al.*, 1991; Anderson and Sinclair, 1993).

Connell (1990) describes two types of interactions among plants. 'Apparent' competition between two plants arises from interactions dependent on a third organism and 'true' competition can result from either of two mechanisms. The first mechanism results from direct interference of one plant with another by direct contact or by the release of allelopathic chemicals into the environment. The second mechanism of competition, which is likely the dominant type of interaction between trees and crops in agroforestry, results from exploitation of a shared resource, so that one plant gains an advantage over a neighbour because it is able to acquire more of a resource that is required for growth and is in limited supply (Grime, 1979; Caldwell, 1987; Connell, 1990). The plant that is more successful at capturing resources will thrive while the less successful plant will experience stress as resources are depleted, so that its growth and productivity are impaired (Nambiar and Sands, 1993). Thus, in the shade of agroforestry trees, growth of crops may be reduced because insufficient sunlight penetrates the foliage of the trees, or where the root systems of trees and crops overlap, extraction of water and nutrients from the soil by trees may cause drought stress or nutrient deficiencies that result in lower crop yields (Ong *et al.*, 1991; Campbell *et al.*, 1994).

Competitiveness depends on both the ability of plants to reduce the availability of resources to neighbours and on the tolerance of plants to depletion of resources (Goldberg, 1990). In order to assess the competitiveness of plants for below-ground resources, it is therefore necessary to determine the rates at which they take up water or nutrients and to determine the responses of neighbouring plants to the consequent availability of resources. When annual crops are grown in agroforestry systems, the trees begin the cropping season with a competitive advantage over the crop because the trees have established root systems that can extract water and nutrients from a large soil volume, while the developing root system of the crop leaves it vulnerable to stress during establishment. If the crop is tolerant of stresses, however, the competitive advantage of the trees is reduced. Hence, the competitive ability of annual crops in agroforestry will depend on their tolerance to shortages of resources and the potential competitiveness of trees for water or nutrients will depend on the rate at which they extract resources from the rooting zone of the crop.

The present study examined the potential competitiveness of tree species for water when grown in windbreaks in the Sahel. Windbreaks are recommended for use in the Sahel to protect soils from wind erosion in areas where the natural vegetation and the population of dispersed trees normally maintained in farmer's fields has become degraded (Harrison, 1987; Rocheleau *et al.*, 1988). Yields of pearl millet (*Pennisetum glaucum* (L.) R. Br.) in fields sheltered by windbreaks are often enhanced (Ujah and Adeoye, 1984; Long, 1989; van den Beldt, 1990) as a result of modification of the microclimate in the lee of the trees, but competition for resources between the trees and millet can reduce the productivity of plants growing near the trees (Brenner, 1991; Brenner *et al.*, 1993; Onyewotu *et al.*, 1994), so that crop production is not increased (Kessler and Breman, 1991; Brenner *et al.*, 1993). Millet is the staple crop of the Sahel and its production is dependent on rain falling during the short annual rainy season. Rainfall in the Sahel is highly variable and can be unreliable (Olsson, 1993; Sivakumar *et al.*, 1993), so that efficient use of soil water in crop production systems in the region is very important (Sivakumar and Wallace, 1991). Consequently, when windbreaks are established it is vital that competition between the trees and millet for water is minimised in order that farmers can realise as much benefit as possible from the improved microclimate of sheltered crops. It is therefore important that the potential competitiveness for water of tree species chosen for inclusion in windbreaks in the Sahel is as low as possible. In order to help advise land-use planners on the most appropriate species for use in windbreaks, the competitiveness for water of three tree species used in agroforestry in the Sahel was assessed by comparing their transpiration rates during the cropping season and by examining patterns of moisture extraction from soil adjacent to windbreaks of each species.

## 2.2 Materials and methods

### 2.2.1 *Site description*

Measurements of tree water use and soil-water extraction were made at a windbreak trial established in 1988 on the research farm of the ICRISAT Sahelian Centre (ISC) at Sadoré (13°14'N, 2°16'E), approximately 45 km south of Niamey, the capital of Niger in West Africa. The climate of this area is typical of the Sahel, with a single, short rainy season which usually begins in June and lasts for three to four months. Mean annual rainfall at Niamey is 545 mm. The remainder of the year is dry and hot, with monthly means of daily maximum temperatures ranging between 33 and 40 °C (Sivakumar *et al.*, 1993). The soil at the site is a sandy (>85%) alfisol (Psammentic Paleustalf) (West *et al.*, 1984) which extends down to a layer of hard laterite at a depth of 3.9 m.

Windbreaks of eight species were growing at the site, arranged with a control (no windbreak) in replicated randomized complete blocks, as shown in Fig. 2.1. Each windbreak ran north-south and was 50 m long, with 30 m of cropland between parallel windbreaks. Each consisted of a double row of alternately planted trees, with 1.5 m between rows and 3 m between trees in the same row. The windbreaks were managed as hedge windbreaks and so were pruned back to 2 m from a height of between 3 and 5 m at the end of every dry season. The height of the windbreaks therefore changed continuously throughout the cropping season (Fig. 2.2) and so the convention in windbreak research of expressing distances from windbreaks as multiples of the height of the trees was not used in this study. Pearl millet (cv. CIVT) was grown between the windbreaks in all years of the study.

Measurements of water use were confined to three of the tree species growing at the site. These were *Azadirachta indica* A. Juss., *Acacia holosericea* A. Cunn. ex G. Don and *Acacia nilotica* ssp. *adstringens* (Schumach. & Thonn.) Roberty. Only *Acacia nilotica* is indigenous to the Sahel, but *Azadirachta indica*, widely known as neem and native to the Indian sub-continent, is common throughout the region (von Maydell, 1990). *Acacia holosericea*, indigenous to northern Australia, has recently been introduced to the region for use in agroforestry (Turnbull, 1988).

### **2.2.2** *Sap flow measurements*

Transpiration was measured in trees of these species using the heat-pulse technique. This technique uses short pulses of heat as a tracer for determining the flux density of sap in woody stems, which is integrated over the cross-sectional area of sapwood in the stems to give sap flow rates (Marshall, 1958; Swanson and Whitfield, 1981; Green and Clothier, 1988; Swanson, 1994). In the method described by Edwards and Warwick (1984), sap fluxes are measured at different depths below the cambium of the tree stem using four sets of implanted heat-pulse probes, with each set of probes comprising a heater and two thermistor probes. The principles underlying the method and the equations used to calculate sap flow are reviewed in Appendix A, which also describes experiments done to determine correction factors that must be applied to measured sap flow rates when the heat-pulse technique is used on the tree species studied here. On the basis of results from these experiments, corrected sap flow rates ($F_c$) were calculated from observed sap flow ($F_h$) using

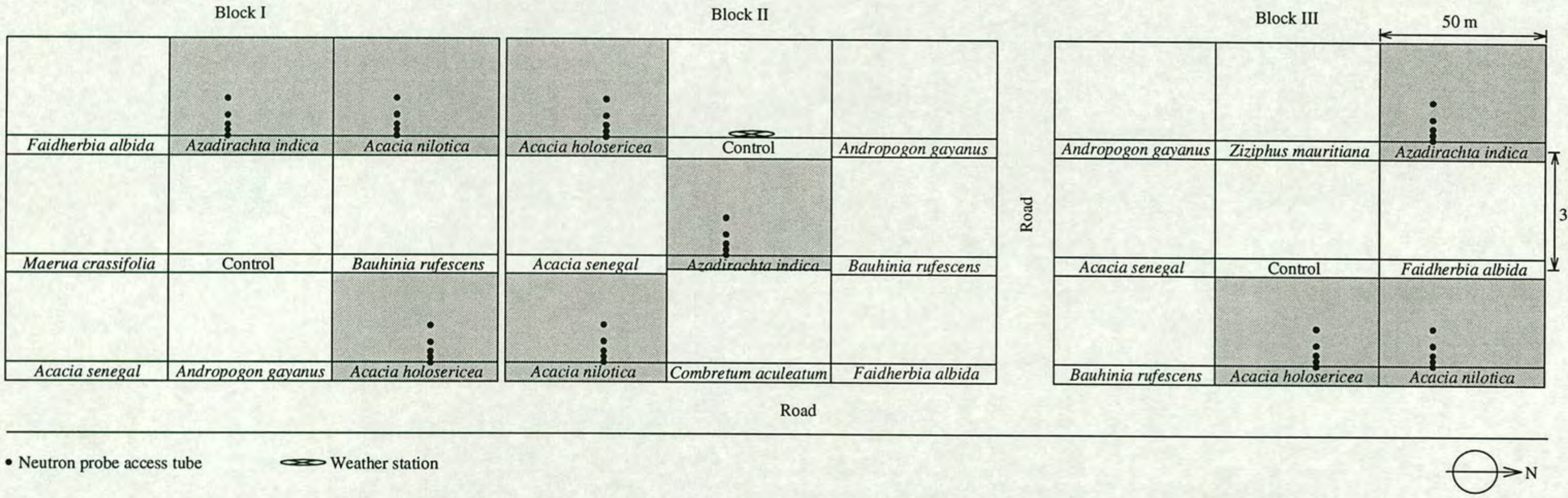

**Figure 2.1:** Layout of the plots at the research station of the ICRISAT Sahelian Centre at Sadoré, Niger used in the study of transpiration and soil-water extraction by tress in windbreaks. Measurements were made on trees of the species in the shaded plots.

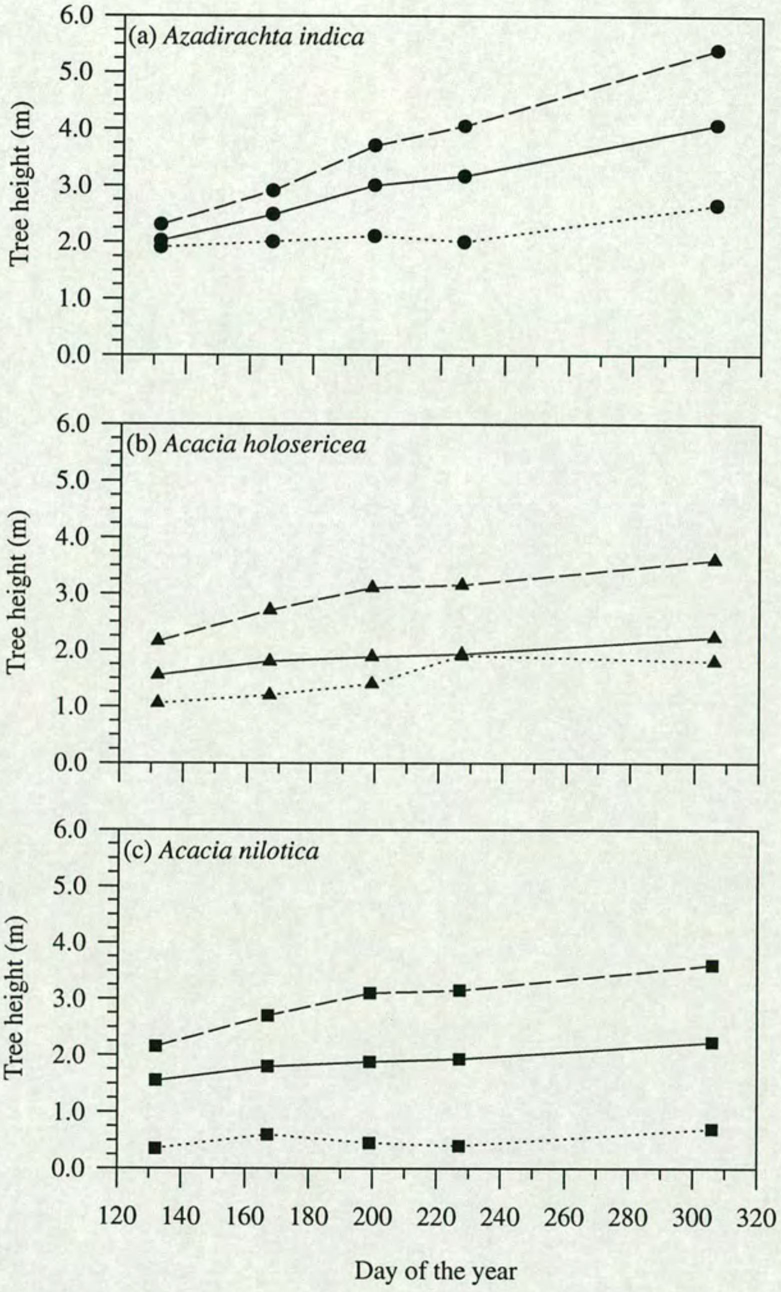

**Figure 2.2:** Mean (———) height of the trees of (a) *Azadirachta indica*, (b) *Acacia holosericea* and (c) *Acacia nilotica* in the hedge windbreaks at Sadoré during 1992. The maximum (— — —) and minimum (·········) tree heights recorded for each species are also shown. Growth of the trees was similar in 1991 and 1993 because all trees were pruned at the end of each dry season, prior to the cropping season.

$$F_c = 1.62\,F_h \qquad \text{for } \textit{Azadirachta indica}, \tag{2.1}$$

$$F_c = 2.43\,F_h \qquad \text{for } \textit{Acacia holosericea} \text{ and} \tag{2.2}$$

$$F_c = 1.85\,F_h \qquad \text{for } \textit{Acacia nilotica}. \tag{2.3}$$

Measurements were replicated three times for each species, with measurements made concurrently on one tree of each species in each block of the experimental layout (Fig. 2.1) during the cropping seasons of 1991, 1992 and 1993. Sap flow was measured in large branches of trees in 1991, whereas, in 1992 and 1993, sap flow was measured for whole trees by implanting the heat-pulse probes into the trunks of the trees studied. The trees in each windbreak on which measurements were made were selected randomly. In 1991, the heat-pulse probes were initially installed on day-of-the-year (DOY) 218 and then re-installed higher up on the same branches approximately every three weeks until measurement ceased on DOY 288. In 1992 and 1993, the probes were moved to different trees at three week intervals. Measurements were made between DOY 161 and 291 in 1992 and over two periods in 1993, first between DOY 171 and 185 and then between DOY 239 and 249. During all of these periods, measurements were made at 20 min intervals and recorded on a heat-pulse logger (Custom HP1, Hort Research, Palmerston North, New Zealand).

### **2.2.3** *Soil moisture measurements*

Volumetric soil moisture content in the vicinity of the windbreaks was measured using a neutron probe between October, 1991 and October, 1992 (Solo 25, Nardeux, St. Avertin, France) and between June and October, 1993 (IH II, Didcot Instrument Co. Ltd., Abingdon, UK.) at approximately weekly intervals during the rainy season and monthly intervals during the dry season. Measurements were made at 0.30 m increments between 0.10 and 2.50 m below the soil surface using 45 mm-diameter aluminium access tubes installed at 0, 1.0, 2.5, 5.0 and 10.0 m from the trunks of trees on the western side of the windbreaks of all three species in each block of the experiment (Fig. 2.1).

### 2.2.4 *Stomatal conductance measurements*

Stomatal conductances of leaves of *Azadirachta indica* and phyllodes of *Acacia holosericea*[*] were measured on several days in 1993, at approximately hourly intervals between 0800 and 1900 using a diffusion porometer (LI-1600, Li-Cor Inc., Lincoln NE, USA.). Measurements were made on both sides of three leaves on a selected tree of each species at each interval.

### 2.2.5 *Leaf area measurements*

In 1991, projected leaf areas ($A_l$) of each branch studied were 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, as described in Appendix B.

In 1992 and 1993, all leaves from each *Azadirachta indica* and *Acacia holosericea* tree studied were harvested after the heat-pulse probes were removed and $A_l$ for each tree estimated from the product of the total dry mass of leaves and specific leaf area, as determined from a subsample of harvested leaves using a leaf area meter (LI-3100, Li-Cor Inc., Lincoln NE, USA.). $A_l$ was not estimated for *Acacia nilotica* trees in 1992 and 1993 because it has sharp thorns which make harvest of its leaves very difficult.

### 2.2.6 *Estimation of projected crown area*

Projected crown area ($A_c$) is the area covered when the crown of a tree is projected on to a horizontal plane (ie. the area of ground within the perimeter of the tree crown). $A_c$ was estimated for each tree studied in 1992 and 1993 following removal of the heat-pulse apparatus. This was accomplished by measuring the radius of each tree crown at 10 points around its perimeter and then plotting these on a scaled diagram. A pencil was used to interpolate between each point and the area of the resulting shape was measured on a leaf area meter. $A_c$ was finally calculated by re-scaling the area of the paper model. The crowns of the trees in the windbreaks formed a closed canopy along the length of the windbreak and the leaf area index ($L$) of each windbreak canopy at the the time at which measurements were made was estimated as $L=A_l/A_c$.

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[*] Foliar elements of *Acacia holosericea* are phyllodes, or modified petioles, rather than true leaves (Turnbull, 1988), but are subsequently referred to as leaves for simplicity.

### **2.2.7** *Other measurements*

Weather conditions were measured in all three years of the study using a weather station at the site (Fig. 2.1). This comprised an anemometer (A100R, Vector Instruments Ltd., Rhyl, UK.) and wind vane (W200, Vector Instruments Ltd., Rhyl, UK.) for measuring wind speed and direction, a solarimeter (CM5, Kipp and Zonen BV., Delft, The Netherlands) to measure incoming solar radiation, a tipping-bucket raingauge (ARG100, Campbell Scientific Ltd., Shepshed, UK.) to measure rainfall and an aspirated psychrometer (Allen *et al.*, 1994) for measuring air temperature and vapour pressure deficit. The raingauge was mounted in a fixed position near the ground and all other instruments were mounted at a height of 4.0 m. All weather data were logged every 30 s and averaged over 10 min intervals using a data logger (21X or CR10, Campbell Scientific Ltd., Shepshed, UK.). For periods when malfunctions occurred and data from the weather station were missing, data from an automated weather station located approximately 1 km away were used instead.

### **2.2.8** *Data analysis*

Sap flow data were rejected after the onset of a response to wounding of the tree caused by implantation of the heat-pulse probes. The onset of such responses was generally observed as a sudden decrease in peak daily sap flow rates, thought to occur because wounding of the wood causes xylem vessels around the implantation site to fill with resin, so that sap movement can no longer be detected.

Measured sap flow rates were corrected using Equations 2.1 to 2.3 and integrated over 24 h to give daily totals for transpiration, which were then normalised on $A_l$ and $A_c$. It was found that variances for daily total transpiration were correlated with means, thus violating the assumption of homogeneity of variance required for the analysis of variance. Daily total sap flow rates were therefore transformed to natural logarithms. Following transformation, variances no longer varied with the mean and an analysis of variance was made on data for each day in order to assess the significance of differences among species. Comparisons between species were made using protected least significance difference tests (Snedecor and Cochran, 1980).

The influence of the windbreaks on soil moisture contents was assessed by making an analysis of variance on the soil moisture data. Distances from windbreaks and depths below the soil surface cannot be randomised and so a repeated measures analysis of variance was used to assess the significance of differences among species on the change of soil water content with distance and depth. Use of the repeated measures procedures ensured that the analyses were not biased as a result of differences in the spatial proximity of the various points of measurement (SAS Institute, 1988; Littell *et al.*, 1991).

### **2.2.9** *Extrapolation of transpiration measurements to seasonal totals*

The record of transpiration by each species during each cropping season was not complete. Thus, in order to estimate total water use by the windbreak trees during the cropping season, it was necessary to extrapolate from measured rates of transpiration. This was done on the basis of the modified Penman-Monteith equation derived by Jarvis and McNaughton (1986) as

$$E = \Omega E_{\mathrm{eq}} + (1 - \Omega) E_{\mathrm{imp}}. \tag{2.4}$$

Here, the evapotranspiration rate, $E$, is the weighted sum of the equilibrium ($E_{\mathrm{eq}}$) and imposed ($E_{\mathrm{imp}}$) rates of evapotranspiration, with $E_{\mathrm{eq}}$, which is a function of net radiation ($R_{\mathrm{n}}$), found from (Jarvis and McNaughton, 1986)

$$E_{\mathrm{eq}} = \frac{s}{\lambda(s + \gamma)} R_{\mathrm{n}} \tag{2.5a}$$

and $E_{\mathrm{imp}}$ given by

$$E_{\mathrm{imp}} = \frac{\rho_{\mathrm{a}} c_p}{\lambda \gamma} g_{\mathrm{c}} D_{\mathrm{a}}, \tag{2.5b}$$

where $s$ is the slope of the saturation vapour pressure curve at the surface temperature, $\gamma$ is the psychrometric constant, $\rho_{\mathrm{a}}$ is the density of air, $c_p$ is the specific heat capacity of dry air at constant pressure, $\lambda$ is the latent heat of vaporisation, $g_{\mathrm{c}}$ is the surface conductance of the vegetation and $D_{\mathrm{a}}$ is the ambient vapour pressure deficit. The magnitude of the weighting factor, $\Omega$, is determined by the degree of coupling between vegetation and the atmosphere and varies between 0 and 1, depending on the relative magnitudes of $g_{\mathrm{c}}$ and the aerodynamic conductance ($g_{\mathrm{a}}$) for the vegetation. For hypostomatous vegetation, $\Omega$ is (Jarvis and McNaughton, 1986)

$$\Omega = \frac{\varepsilon + 2}{\varepsilon + 2 + g_a / g_c}, \tag{2.6}$$

where $\varepsilon = s/\gamma$.

To extrapolate the measured transpiration rates for windbreaks to seasonal water use, it was assumed that $g_c = Lg_s$ and Equations 2.4 and 2.5b were combined to give

$$E = \Omega E_{eq} + \left( (1 - \Omega) \frac{\rho_a c_p}{\lambda \gamma} D_a L \right) g_s, \tag{2.7}$$

where $g_s$ is stomatal conductance per unit leaf area. For a particular set of conditions, Equation 2.7 is a linear equation of the form:

$$E = c + \nu \hat{g}_s \tag{2.8}$$

where $\nu$ is a composite variable given by

$$\nu = (1 - \Omega) \frac{\rho_a c_p}{\lambda \gamma} D_a L, \tag{2.9}$$

$c$ is the intercept term and $\hat{g}_s$ is the slope term. Comparison of Equations 2.7 and 2.8 shows that $c$ is an estimate of $\Omega E_{eq}$ and that $\hat{g}_s$ represents an effective stomatal conductance. Equation 2.8 was used to extrapolate from measured transpiration rates to seasonal water use.

For hedge windbreaks of *Azadirachta indica* at Sadoré, $\Omega$ was estimated using an empirical function derived from values of $\Omega$ determined using aerodynamic and surface conductances that were measured during experiments in which environmental and physiological control of transpiration by windbreaks was examined, as described in Chapter 6. These experiments showed that $\Omega$ was $\approx 0.3$ at moderate wind speeds during the middle of the day. Non-linear regression was used to fit Equation 2.6 to these measured values of $\Omega$, as shown in Appendix C, with the influence of $g_a$ on $\Omega$ represented by a function of wind speed ($u$) and the influence of $g_c$ represented by a function of incoming solar radiation ($R_s$) and $D_a$, with the result that

$$\Omega = \frac{\varepsilon + 2}{\varepsilon + 2 + \left[ \frac{(0.30 + 1.1u^{1.1})(1.0 + (0.0044(R_s + 44))}{0.59(0.0044(R_s + 44))(1.0 - 0.18D_a)} \right]}. \tag{2.10}$$

This equation was thus derived from data measured independently of the sap flow measurements of transpiration made as described in Section 2.2.2 and, with $\varepsilon$ evaluated at air temperature, it can be used to estimate values of $\Omega$ for hedge windbreaks of *Azadirachta indica* at Sadoré from meteorological data. Values of $\Omega$ for windbreaks of other species at the site can be estimated using the same equation under the reasonable assumption that coupling of windbreaks of each species to the atmosphere is similar.

To model $c$ and $\hat{g}_s$, Equation 2.10 was used to estimate $\Omega$ for each hourly rate of transpiration per unit projected crown area measured in 1992 and 1993 for *Azadirachta indica* and *Acacia holosericea* windbreaks and a value of $\nu$ was then determined from Equation 2.9. Non-linear regression was used to fit Equation 2.8 to these transpiration data for each species, but with $c$ and $\hat{g}_s$ replaced by functions of environmental variables. The intercept term $c$ was modelled using

$$c = \Omega(\alpha_1 R_s L), \tag{2.11}$$

where $\alpha_1$ is a regression coefficient, so that the dependency of $E_{eq}$ on $R_n$ was approximated by a function of $R_s$ and $L$. The approach described by Jarvis (1976) was used to model $\hat{g}_s$, so that

$$\hat{g}_s = \beta_1(\hat{g}_s(R_s)\hat{g}_s(D_a)), \tag{2.12a}$$

where $\beta_1$ represents the maximum value of $\hat{g}_s$ and $\hat{g}_s(R_s)$ and $\hat{g}_s(D_a)$ are functions giving relative changes in $\hat{g}_s$ in response to $R_s$ and $D_a$ with the form

$$\hat{g}_s(R_s) = \frac{\beta_2(R_s - \beta_3)}{1.0 + \beta_2(R_s - \beta_3)} \quad \text{and} \tag{2.12b}$$

$$\hat{g}_s(D_a) = 1.0 + \beta_4 D_a, \tag{2.12c}$$

where $\beta_2$, $\beta_3$ and $\beta_4$ are regression coefficients. The resulting models of $c$ and $\hat{g}_s$ for *Azadirachta indica* and *Acacia holosericea* allowed variation of the intercept and slope terms of Equation 2.8 in response to environmental conditions to be determined for each species.

Values of $L$ required in calculations of seasonal water use by windbreaks were estimated from

$$L = -2.02 + 0.0258 d_y \quad \text{for } \textit{Azadirachta indica} \text{ and} \tag{2.13}$$

$$L = -3.42 + 0.0276 d_y \quad \text{for } \textit{Acacia holosericea}, \tag{2.14}$$

where $d_y$ is day of the year. Equations 2.13 and 2.14 were derived using multiple regression from data collected from the leaf harvests of the trees studied in 1992 and 1993 and give values of $L$ for trees in the windbreaks with mean trunk diameter.

These models of $\Omega$, $\hat{g}_s$, $c$ and $L$ were then used to extrapolate measured rates of transpiration by the windbreaks to seasonal transpiration on a physiological basis. Each was substituted into Equation 2.8, which was then used to calculate hourly estimates of transpiration from hourly averages of meteorological data during each day of the cropping seasons of 1992 and 1993, where the cropping season was defined as the period between sowing and maturity of the millet crop at the site. Finally, estimates of transpiration during the cropping seasons of 1992 and 1993 by windbreaks of *Azadirachta indica* and *Acacia holosericea* were calculated by summing the estimates of hourly transpiration over all days in each season. A similar analysis of transpiration by *Acacia nilotica* was not made because leaf areas for this species were not measured in 1992 or 1993.

## 2.3 Results and discussion

### **2.3.1** *Differences in transpiration rates among species*

Transpiration per unit leaf area over the course of DOY 233, 1991 is shown in Fig. 2.3 for branches of *Azadirachta indica*, *Acacia holosericea* and *Acacia nilotica* trees in windbreaks. These data are typical of days on which measurements were made in 1991 and show that, on the basis of leaf areas, transpiration rates during the middle of the day tended to be relatively high for *Acacia holosericea* but relatively low for *Azadirachta indica*. However,

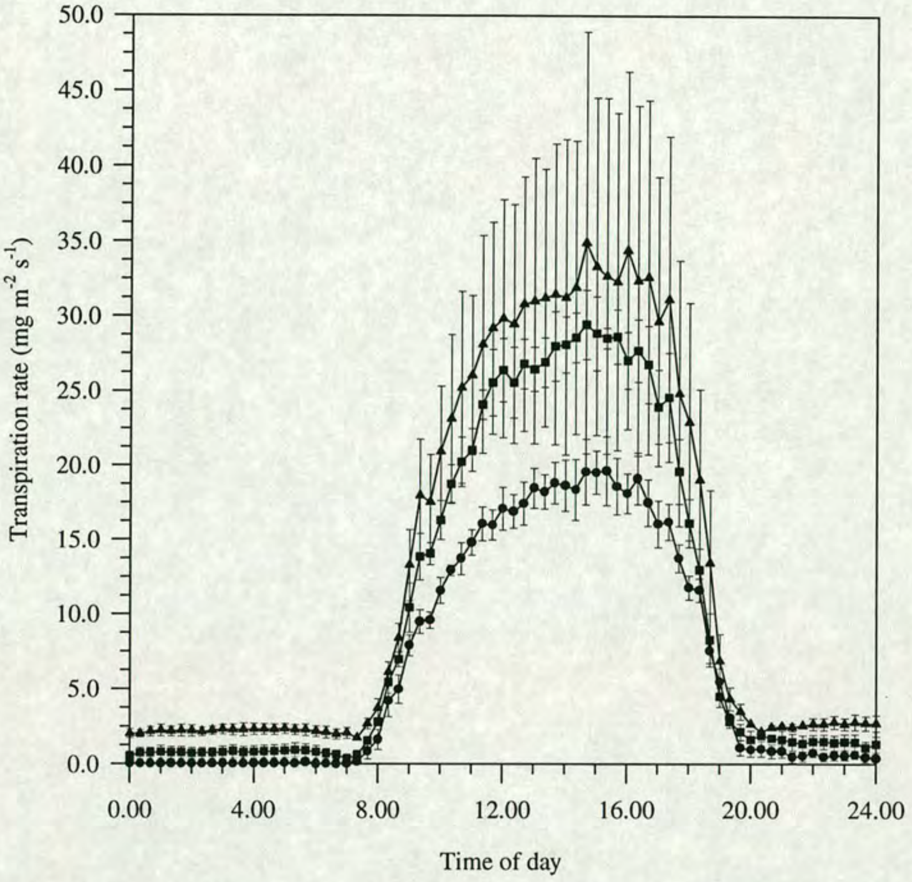


**Figure 2.3:** Rates of transpiration per unit leaf area for branches of *Azadirachta indica* (n=3) (●), *Acacia holosericea* (n=2) (▲) and *Acacia nilotica* (n=3) (■) trees in windbreaks on DOY 233, 1991, at Sadoré, Niger. Error bars show ±1 s.e.

the standard error bars on the data points attest to the high level of inter-tree variability in transpiration rates for each species and demonstrate that measurements need to be well replicated in order for differences in water use among species to be statistically significant. Measurements were replicated three times in this experiment, but it proved to be very difficult to make concurrent measurements in all replications because wound reactions in the woody tissue of the species studied often developed within only a few days of implanting the heat-pulse probes.

There was one period in 1991, between DOY 222 and 249, when concurrent measurements of transpiration were made on three trees of *Azadirachta indica* and *Acacia nilotica* and on two trees of *Acacia holosericea* on most days, so that daily total transpiration by each species could be compared statistically. Results of these comparisons are given in Table 2.1 for DOY 225 to 239, 1991, and show that, on most days in this period, transpiration

**Table 2.1:** Daily total transpiration per unit leaf area for branches of *Azadirachta indica*, *Acacia holosericea* and *Acacia nilotica* trees in windbreaks between DOY 225 and 239, 1991. Values in the same row followed by the same letter are not significantly different ($P<0.05$).

| | Daily Transpiration (kg $m^{-2}$ $d^{-1}$) | | |
|---|---|---|---|
| DOY | *Acacia holosericea*<br>n=2 | *Acacia nilotica*<br>n=3 | *Azadirachta indica*<br>n=3 |
| 225 | 1.51 a | 1.19 a | 0.74 a |
| 226 | 1.24 a | 0.97 a | 0.61 b |
| 227 | 1.53 a | 1.23 a | 0.79 b |
| 228 | 1.39 a | 1.08 a | 0.70 a |
| 229 | 1.02 a | 0.77 a | 0.48 b |
| 230 | 0.81 a | 0.54 a | 0.34 b |
| 231 | 1.27 a | 0.93 a | 0.63 b |
| 232 | 0.49 a | 0.27 b | 0.14 c |
| 233 | 1.16 a | 0.89 ab | 0.59 b |
| 234 | 1.30 a | 0.97 a | 0.65 a |
| 235 | 0.61 a | 0.46 a | 0.28 b |
| 236 | 1.03 a | 0.93 a | 0.62 b |
| 237 | 1.11 a | 1.05 a | 0.72 b |
| 238 | 1.15 a | 0.83 a | 0.56 b |
| 239 | 1.37 a | 1.02 ab | 0.71 b |
| mean | 1.13 | 0.88 | 0.57 |

per unit leaf area was significantly ($P<0.05$) less for *Azadirachta indica* than either *Acacia holosericea* or *Acacia nilotica*. Measurements were not well replicated in 1992 and 1993, but the mean values of all daily transpiration measurements were 0.73 and 1.25 kg $m^{-2}$ $d^{-1}$ in 1992 and 1.20 and 1.69 kg $m^{-2}$ $d^{-1}$ in 1993 for *Azadirachta indica* and *Acacia holosericea*, respectively, thus lending support to the conclusion from 1991 that *Azadirachta indica* uses less water than the other species studied. These observations suggest that *Azadirachta indica* is less competitive with adjacent crops for water than either *Acacia holosericea* or *Acacia nilotica*, although the impact of demand for water by the trees on the availability of water to the crop will also depend on from where in the soil profile the water is extracted.

### **2.3.2** *Differences in stomatal conductances among species*

Rainfall during the period DOY 225 to 239, 1991, was 94 mm and so soil-moisture availability probably did not limit transpiration in any of the species. Ambient

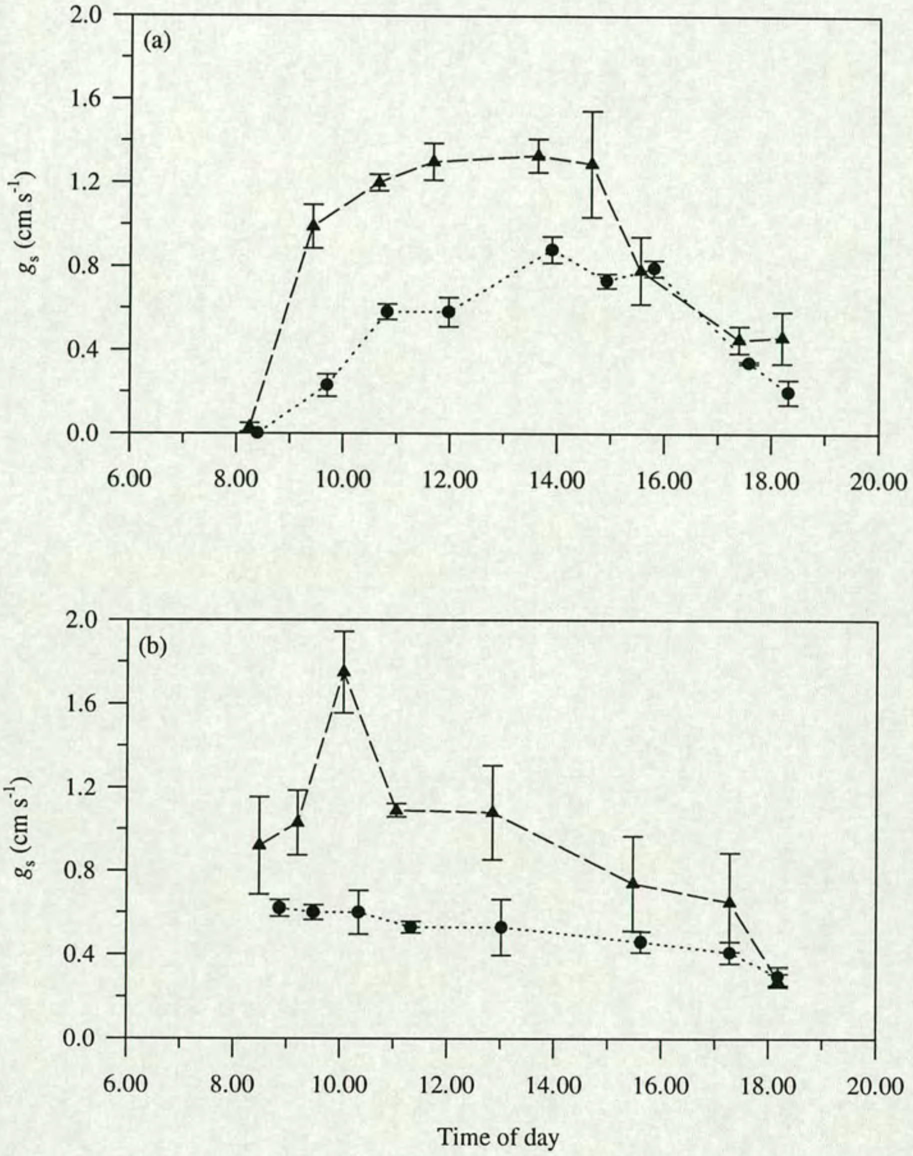


**Figure 2.4:** Stomatal conductances (n=3) on a projected leaf area basis of *Azadirachta indica* (●) leaves and *Acacia holosericea* (▲) phyllodes on (a) DOY 181 and (b) DOY 183, 1993. The morning of DOY 181 was overcast while DOY 183 was bright for the whole day. Error bars show ±1 s.e.

atmospheric conditions were the same for each species, so the observed differences in transpiration per unit leaf area must reflect differences among species intrinsic to the trees or windbreaks. As shown in Fig. 2.4, stomatal conductances of leaves tended to be lower for the hypostomatous *Azadirachta indica* than the amphistomatous *Acacia holosericea* through most of the day when measured in 1993, suggesting that differences among species in transpiration rates may have been caused by differences in leaf characteristics and stomatal physiology. It may be possible, therefore, to assess relative water use among species considered suitable for use in windbreaks simply by comparing their stomatal conductances, provided that, first, it is demonstrated that trees in windbreaks are well coupled to the atmosphere, so that they are able to exert physiological control over transpiration and, second, that tree species tested in this way are growing in windbreaks under matching conditions and with similar total leaf areas.

### **2.3.3** *Extrapolation of daily water use to seasonal water use*

Estimates of the values of the regression coefficients used in Equations 2.11, 2.12a, 2.12b and 2.12c to estimate hourly rates of transpiration per unit projected crown (ie. ground) area on the basis of Equation 2.8 are given in Table 2.2. The apparent responses of modelled values of $\hat{g}_s$ to solar radiation and ambient vapour pressure deficit are shown in Fig. 2.5a for *Azadirachta indica* and in Fig 2.5b for *Acacia holosericea*. Values of $\hat{g}_s$ increased as illumination of the trees increased, but decreased as $D_a$ increased, and under matching conditions, values of $\hat{g}_s$ were higher for *Acacia holosericea* than *Azadirachta indica*, reflecting the differences between these species in values of stomatal conductances measured with the porometer (Fig. 2.4).

**Table 2.2:** Values of regression coefficients determined by using non-linear regression to fit Equation 2.8, $E = c + \nu \hat{g}_s$, to plots of measured, hourly rates of transpiration ($E$) per unit projected crown area against the composite variable, $\nu$, for trees of *Azadirachta indica* and *Acacia holosericea* in windbreaks, with Equation 2.11 (coefficient $\alpha_1$) used to model the intercept term, $c$, and Equations 2.12a, 2.12b and 2.12c (coefficients $\beta_1$, $\beta_2$, $\beta_3$ and $\beta_4$) used to model $\hat{g}_s$, the slope term and an effective stomatal conductance. The values of $R^2$ are the coefficients of determination for the fitted equations for each species.

| | Species | | | |
|---|---|---|---|---|
| Coefficient | *Azadirachta indica* | | *Acacia holosericea* | |
| $\alpha_1$ (kg $W^{-1}$ $h^{-1}$) | $7.7 \times 10^{-5}$ | $\pm 8.4 \times 10^{-6}$ | $9.5 \times 10^{-5}$ | $\pm 1.3 \times 10^{-5}$ |
| $\beta_1$ (m $h^{-1}$) | 11.8 | ±0.64 | 16.2 | ±0.85 |
| $\beta_2$ ($m^2$ $W^{-1}$) | 0.011 | ±0.0019 | 0.021 | ±0.0045 |
| $\beta_3$ (W $m^{-2}$) | -11.3 | ±2.2 | -7.8 | ±1.8 |
| $\beta_4$ ($kPa^{-1}$) | -0.16 | ±0.0043 | -0.15 | ±0.0046 |
| $R^2$ | 0.67 | | 0.62 | |

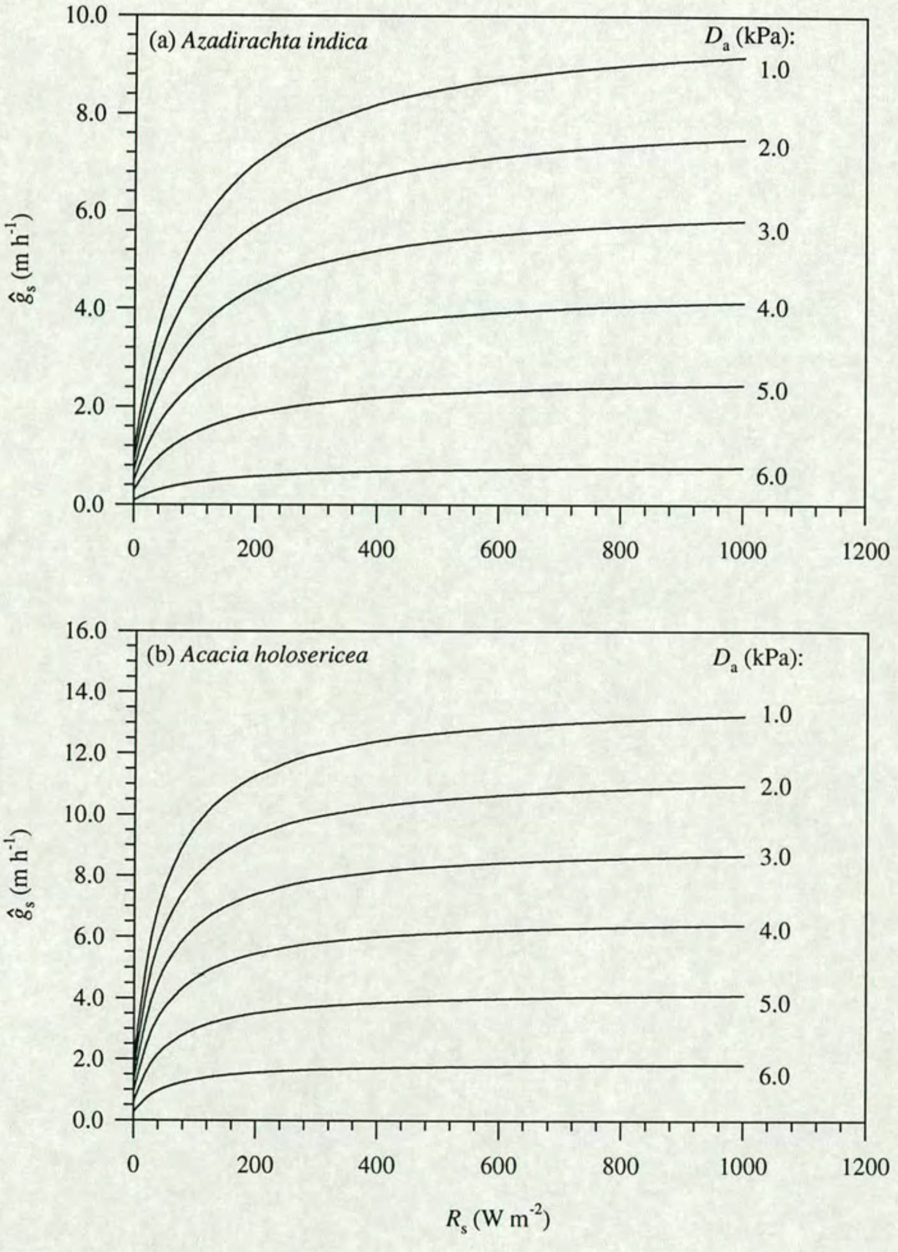


**Figure 2.5:** The response of the slope term of Equation 2.8, the effective stomatal conductance $\hat{g}_s$, to solar radiation ($R_s$) at several levels of the ambient vapour pressure deficit ($D_a$) for trees of (a) *Azadirachta indica* and (b) *Acacia holosericea* in windbreaks. The curves were calculated using Equations 2.12a, 2.12b and 2.12c and the coefficients $\beta_1$, $\beta_2$, $\beta_3$ and $\beta_4$ in Table 2.2.

Observed values of daily transpiration determined from transpiration rates measured using the heat pulse method are plotted in Fig. 2.6a for 1992 and Fig. 2.7a for 1993, together with estimates of daily transpiration by windbreaks of *Acacia holosericea* and *Azadirachta indica* computed using Equations 2.8 to 2.12 from weather data, the coefficients in Table 2.2 and estimates of $L$ made with Equations 2.13 and 2.14. Estimated daily transpiration fluctuated throughout the cropping season of both years because of variations in insolation and $D_a$ and so a 5 d moving average of estimated daily transpiration for each season is plotted in Figs. 2.6b and 2.7b in order to highlight trends over the seasons in water use by the trees. Early in the cropping seasons of both years, estimated daily transpiration was low (Figs 2.6b and 2.7b), despite very high values of $D_a$ (Figs. 2.6c and 2.7c), because the amount of leaf area on the windbreak trees was low (Figs. 2.6c and 2.7c) as a result of shedding of leaves during the dry season and pruning of the trees prior to the onset of the rains. As shown in Figs. 2.6b and 2.7b, daily transpiration appears to have been highest towards the end of each cropping season in both species as a result of increasing vapour pressure deficits and expansion of $L$.

### **2.3.4** *The effects of pruning on tree water use*

Measurements made by Brenner (1991) showed that water use by *Azadirachta indica* windbreaks in the Sahel was high at the start of the cropping season. He found that transpiration by the trees was almost 4 mm $d^{-1}$ at the beginning of the season and then dropped to less than 3 mm $d^{-1}$ for most of the period of crop growth before rising again to 4 mm $d^{-1}$ at the end of the season. The windbreaks studied by Brenner were 6 m tall, whereas the trees studied here varied in height from 2 m up to approximately 5 m (Fig. 2.2), and so it is difficult to compare the rates of transpiration measured by Brenner directly with those reported here because of the considerable difference in the size of the trees. Brenner's windbreaks were not pruned, so that the difference between the two sets of observations in water use by the trees early in the cropping season relative to later in the season indicates that pruning of windbreaks prior to sowing of the crop can reduce demand for water by the trees. Pruning can thus be employed to limit transpiration by windbreaks during the early stages of crop growth, when evaporative demand is high but water is often in short supply because the rainy season is not well advanced. During this period the millet crop has a small root system and so is especially vulnerable to dry spells, which will affect the crop more severely if competition for water from the trees is acute. Pruning of windbreaks therefore reduces the competitive advantage held by the trees during the period of crop establishement as a result of their perennial root systems.

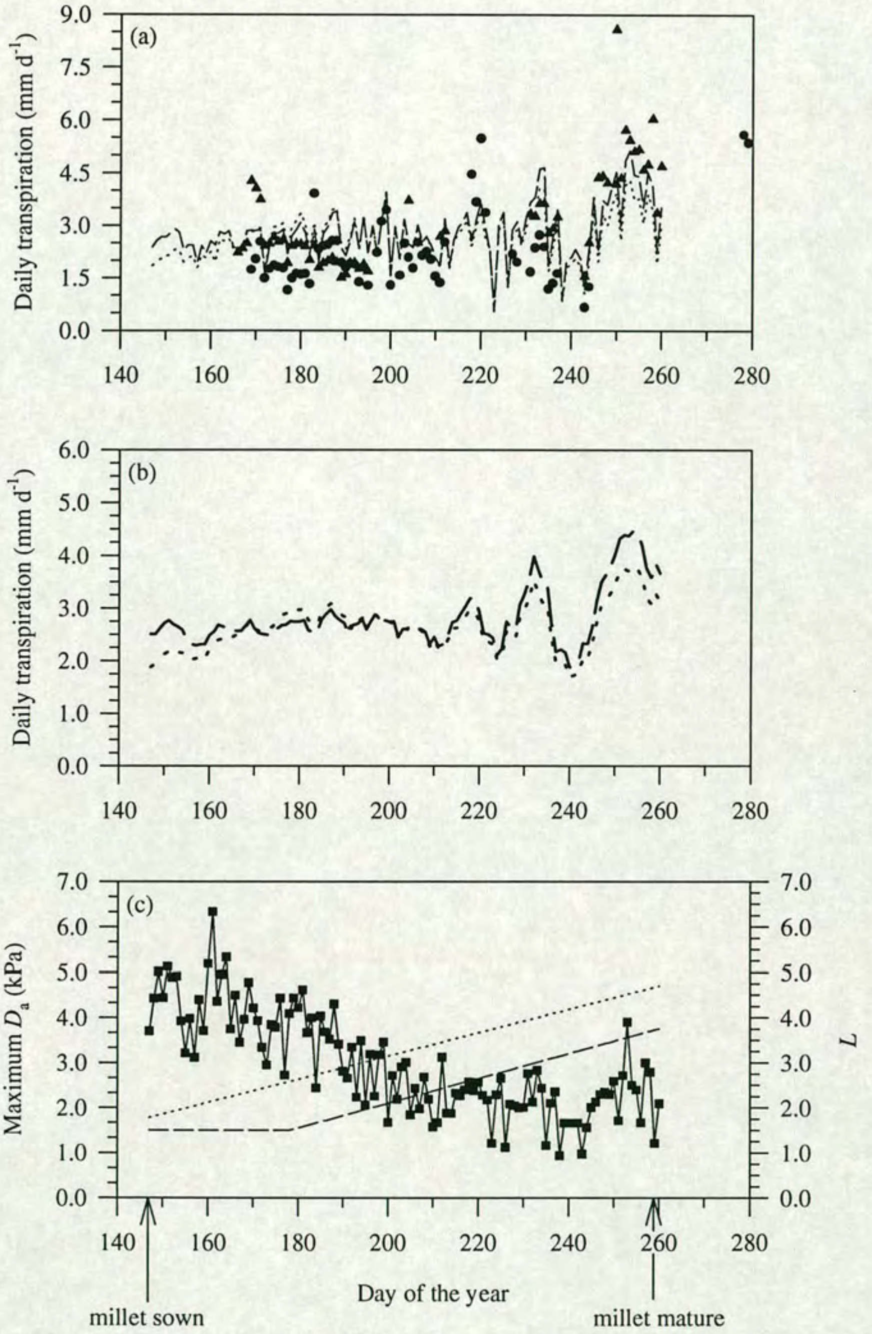


**Figure 2.6:** (a) Estimated (lines) and measured (symbols) daily transpiration for windbreaks of *Azadirachta indica* (········ and ●) and *Acacia holosericea* (——— and ▲) between sowing (DOY 147) and maturity (DOY 259) of adjacent millet in 1992. (b) 5 d moving average of estimated daily transpiration for windbreaks of *Azadirachta indica* (········) and *Acacia holosericea* (———). (c) Daily maximum vapour pressure deficit ($D_a$) (■) and leaf area indices ($L$) for *Azadirachta indica* (········) and *Acacia holosericea* (———) windbreaks estimated using Equations 2.13 and 2.14, with the minimum value for *Acacia holosericea* set at $L$=1.5, the lowest value observed.

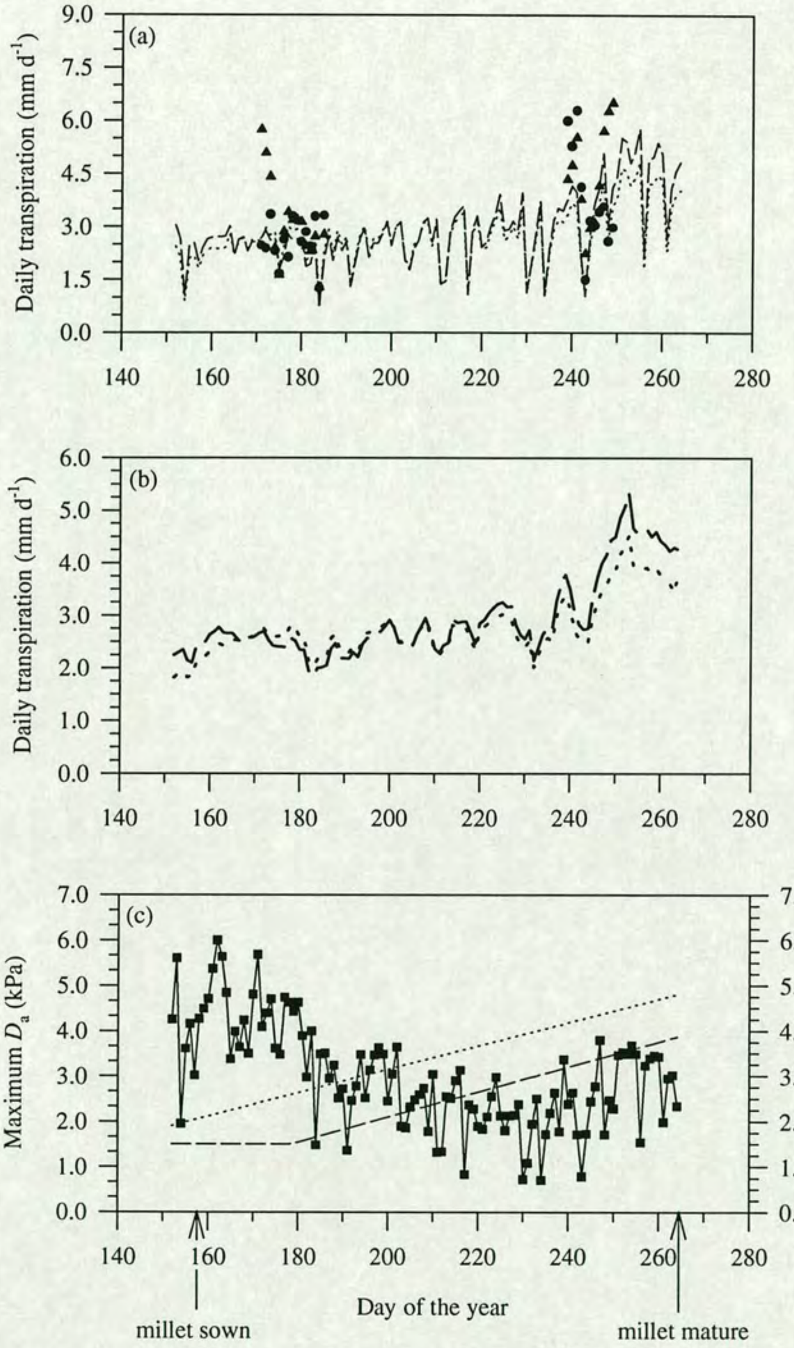


**Figure 2.7:** (a) Estimated (lines) and measured (symbols) daily transpiration for windbreaks of *Azadirachta indica* (········ and ●) and *Acacia holosericea* (——— and ▲) between sowing (DOY 157) and maturity (DOY 264) of adjacent millet in 1993. (b) 5 d moving average of estimated daily transpiration for windbreaks of *Azadirachta indica* (········) and *Acacia holosericea* (———). (c) Daily maximum vapour pressure deficit ($D_a$) (■) and leaf area indices ($L$) for *Azadirachta indica* (········) and *Acacia holosericea* (———) windbreaks estimated using Equations 2.13 and 2.14, with the minimum value for *Acacia holosericea* set at $L$=1.5, the lowest value observed.

**Table 2.3:** Estimated total transpiration in 1992 and 1993 for hedge windbreaks of *Azadirachta indica* and *Acacia holosericea* at Sadoré, Niger between sowing and maturity of the millet crop (cropping season).

| Year | Period of Cropping Season | Species | Estim. Total Transpiration (mm) | Annual Rainfall (mm) |
|---|---|---|---|---|
| 1992 | DOY 147-259 | *Azadirachta indica* | 298 | 579 |
| | | *Acacia holosericea* | 317 | |
| 1993 | DOY 157-264 | *Azadirachta indica* | 302 | 534 |
| | | *Acacia holosericea* | 320 | |

A disadvantage of pruning is that the extent of the zone sheltered by the windbreaks is reduced if the trees are shortened. This is an important concern because millet seedlings are vulnerable during the days following emergence to burial by sand blown by the strong winds which often precede rainstorms in the Sahel (Michels *et al.*, 1993). Consequently, research is required to identify optimal pruning strategies which minimise demand for water by windbreaks during prescribed periods while maximising the extent of the zone sheltered by the trees. Schemes for the management of windbreak trees involving pruning thus require testing before they can be recommended to farmers and development agents.

### **2.3.5** *Total tree water use during the cropping season*

Water use by the *Azadirachta indica* and *Acacia holosericea* windbreaks during the cropping seasons of 1992 and 1993 was estimated by summing the daily estimates of transpiration shown in Figs. 2.6a and 2.7a between sowing and maturity of the millet crop. The resulting seasonal totals are given in Table 2.3. Total water use during the cropping season was larger for *Acacia holosericea* than *Azadirachta indica* in both years, reflecting the differences between the species in transpiration per unit leaf area. The differences between the two species were, however, higher per unit leaf area than when totalled over the season on the basis of projected crown area because *L* tended to be smaller for *Acacia holosericea* than for *Azadirachta indica*. The differences between the species demonstrate that *Acacia holosericea* uses more water than *Azadirachta indica* over the cropping season and so may compete more strongly with crops for water if it extracts water from the root zone of the crop.

### **2.3.6** *Extraction of soil water by windbreak trees*

Volumetric soil water contents ($\theta_v$) between windbreaks of each species and a distance of 10 m into the millet field are shown in Figs. 2.8 and 2.9 at depths of 0.4, 1.0 and 1.6 m for a selection of days from the cropping seasons of 1992 and 1993. Summaries of the results of the analyses of variance of the soil water data for these days are given in Tables 2.4 and 2.5. These results demonstrate that in both years, the effect of the windbreaks on $\theta_v$ varied significantly among the three species studied, although there were occasions when differences were not significant and the effect of species was more pronounced in 1993 than 1992.

#### *Influence of tree species on $\theta_v$ in 1992*

On the day that the millet crop at the site was sown in 1992 (DOY 147), most water was in the top layer of the soil profile (not shown) and differences among species in their influence on $\theta_v$ were small, even if significant (Table 2.4). By DOY 161, 1992, water had penetrated to lower levels of the soil profile (Fig. 2.8B) and the effect of proximity to the windbreak on $\theta_v$ differed significantly among species (Table 2.4). Soil adjacent to *Azadirachta indica* trees was more moist than soil close to either *Acacia holosericea* or *Acacia nilotica* at the 0.4 m depth (Fig. 2.8B). It also appears that water had penetrated more deeply near the *Azadirachta indica* trees than near the windbreaks of the other species, suggesting that *Acacia holosericea* and *Acacia nilotica* were extracting more water from shallow layers of the soil.

Measurements of $\theta_v$ were not repeated in 1992 until DOY 217 because of a fault in the Solo 25 neutron probe. This date was just 4 d after rainfall of 68 mm which made the soil profile very wet (Fig. 2.8C), so that differences in $\theta_v$ resulting from extraction of soil water by the trees did not occur (Table 2.4). On DOY 230, there was also little evidence of water extraction by the trees in the $\theta_v$ data because the soil profile remained wet throughout the intervening period as a result of over 110 mm of rain in four main rainfall events. There was, however, a significant interaction between distance from the trees and species on this date (Table 2.4) and Fig. 2.8D shows that at the 1.6 m depth, the soil was drier adjacent to the windbreaks of *Acacia holosericea* than close to the windbreaks of either *Azadirachta indica* or *Acacia nilotica*. Comparison of $\theta_v$ data from DOY 217 and DOY 230 (Figs. 2.8C and 2.8D) shows that this difference probably arose because less water infiltrated to the 1.6 m depth at 0, 1.0 and 2.5 m from the *Acacia holosericea* trees, as would be expected if they were extracting

**Table 2.4:** Summary of the results of the repeated measures analysis of variance of volumetric soil moisture contents measured on selected days from the cropping season of 1992 at an array of depths below the soil surface and distances from the trunks of trees of *Azadirachta indica*, *Acacia holosericea* and *Acacia nilotica* in windbreaks. Significance levels are shown for the main effect of species and interactions with distance and depth. (NS=P>0.05).

| | P< | | | | |
|---|---|---|---|---|---|
| Source of variation | Day of the Year 147 | 161 | 217 | 230 | 279 |
| Species | NS | NS | NS | NS | NS |
| Species x Distance | NS | 0.01 | NS | 0.05 | NS |
| Species x Distance x Depth | 0.001 | NS | NS | NS | NS |

more water from shallow layers of the soil. Despite this effect, it is improbable that water use by any of the species had any influence on the availability of water to the crop during this period because there was sufficient rainfall to keep the soil very moist at most depths. Thus, during periods, or years, when rainfall is plentiful, differences in competitiveness for water among tree species are likely to have little influence on the water status and yields of crops behind windbreaks.

The final day from 1992 for which data are presented, DOY 279 (Fig. 2.8E), occurred after the crop reached physiological maturity on DOY 259, during the early part of the dry season when the soil profile was drying. There was no significant effect of species on this day (Table 2.4), but Fig. 2.8E shows that soil near the *Azadirachta indica* windbreaks was drying more slowly at all depths in comparison to soil close to the two *Acacia* species.

### *Influence of tree species on $\theta_v$ in 1993*

The first day in 1993 for which data are illustrated in Fig. 2.9 is DOY 183, several weeks after the millet was sown on DOY 150. Differences among species in their influence on $\theta_v$ were significant (Table 2.5), with more water present in the soil adjacent to trees of *Azadirachta indica* than near the *Acacia nilotica* or *Acacia holosericea* windbreaks (Fig. 2.9A). Differences among species were similar on DOY 211 (Table 2.5 and Fig. 2.9B) and examination of changes in $\theta_v$ between DOY 183 and 211 demonstrates that rewetting of

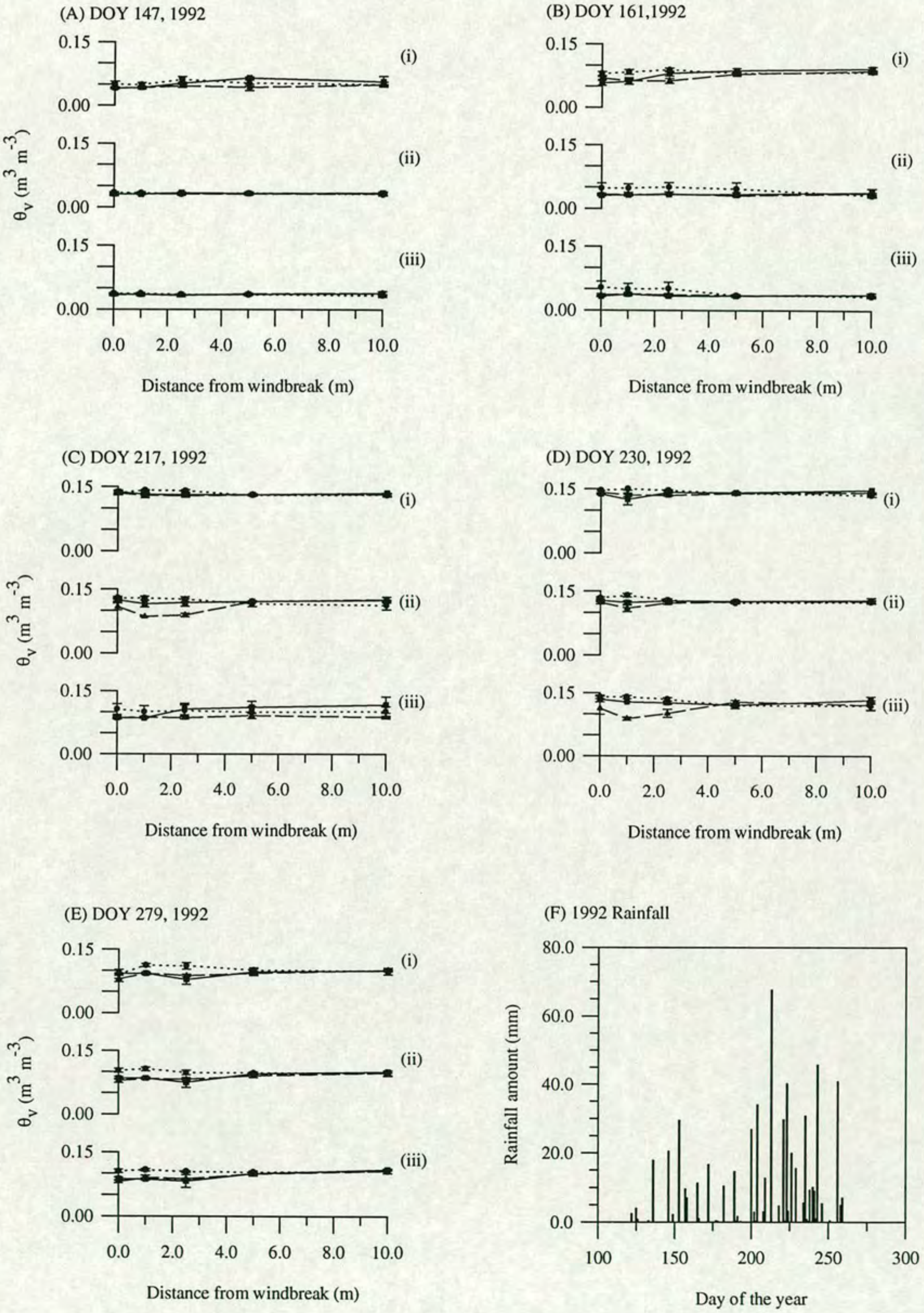


**Figure 2.8:** (A-E) Volumetric moisture content ($\theta_v$) of soil at (i) 0.4 m, (ii) 1.0 m and (iii) 1.6 m below the soil surface at several distances from the trunks of *Acacia nilotica* (■——■), *Acacia holosericea* (▲– –▲) and *Azadirachta indica* (●······●) trees in hedge windbreaks at Sadoré, Niger, on selected days from the cropping season of 1992. Error bars show ±1 s.e. (F) Rainfall at Sadoré in 1992.

**Table 2.5:** Summary of the results of the repeated measures analysis of variance of volumetric soil moisture contents measured on selected days from the cropping season of 1993 at an array of depths below the soil surface and distances from the trunks of trees of *Azadirachta indica*, *Acacia holosericea* and *Acacia nilotica* in windbreaks. Significance levels are shown for the main effect of species and interactions with distance and depth. (NS=P>0.05).

| | P< | | | | |
|---|---|---|---|---|---|
| Source of variation | Day of the Year 183 | 211 | 232 | 249 | 274 |
| Species | NS | NS | 0.01 | 0.01 | 0.05 |
| Species x Distance | 0.0001 | 0.05 | 0.0001 | 0.001 | 0.05 |
| Species x Distance x Depth | NS | NS | 0.0001 | 0.001 | NS |

the soil up to at least 2.5 m from the trees was slower in plots sheltered by the *Acacia holosericea* and *Acacia nilotica* windbreaks than in plots next to windbreaks of *Azadirachta indica.*

As the 1993 rainy season advanced, this effect became more pronounced, so that by DOY 232, $\theta_v$ below 0.4 m was much higher adjacent to the *Azadirachta indica* trees than either of the *Acacia* species (Fig. 2.9C). The soil at 0.4 m was uniformly moist for all species because 45 mm of rain had fallen over the preceeding 3 d, but values of $\theta_v$ below this depth represent a record of differences among species in soil water status during the foregoing period, between approximately DOY 200 and 225, when rainfall was low and infrequent (Fig. 2.9F). Comparison of $\theta_v$ data at depths of 1.0 and 1.6 m between DOY 183 and 232 shows that the water contents of soil at 0, 1.0 and 2.5 m from *Acacia holosericea* and *Acacia nilotica* trees barely increased because water did not infiltrate through the top layers of the soil. Thus, when rainfall is not plentiful, windbreak trees can substantially reduce the amount of water available to neighbouring crops and the magnitude and lateral extent of this reduction depends on the species of tree used in the windbreak.

These differences in $\theta_v$ values among species persisted until DOY 249 (Fig. 2.9D), although only at depths below 1.0 m because of infiltration of further rainfall. Following the end of the rainy season, after the millet reached physiological maturity on DOY 264, drying of the soil profile was similar to that seen at the same time of year in 1992. In 1993, however, differences among species were significant (Table 2.5), with soil adjacent to

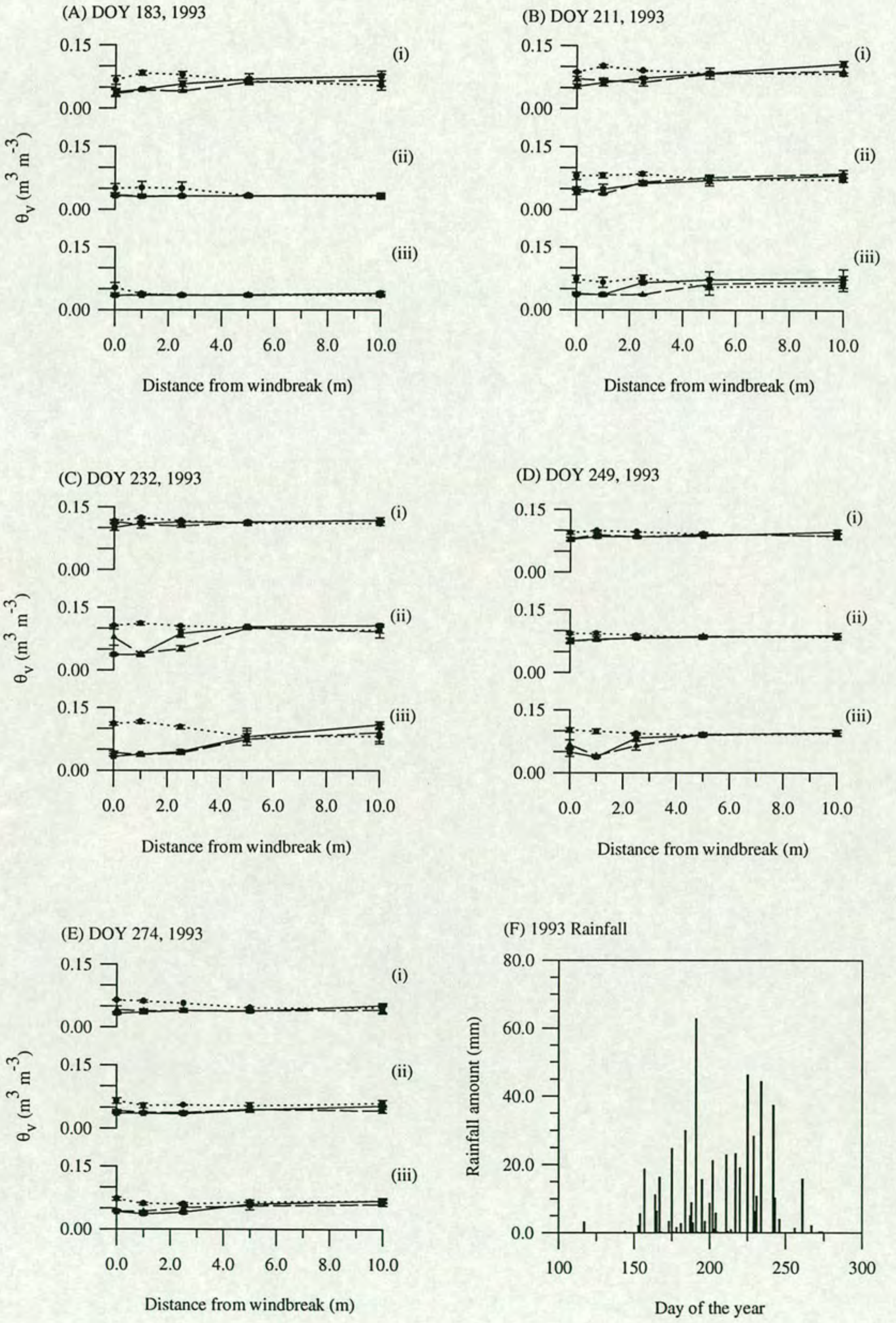


**Figure 2.9:** (A-E) Volumetric moisture content ($\theta_v$) of soil at (i) 0.4 m, (ii) 1.0 m and (iii) 1.6 m below the soil surface at several distances from the trunks of *Acacia nilotica* (■——■), *Acacia holosericea* (▲— —▲) and *Azadirachta indica* (●······●) trees in hedge windbreaks at Sadoré, Niger, on selected days from the cropping season of 1993. Error bars show ±1 s.e. (F) Rainfall at Sadoré in 1993

the windbreaks of *Acacia holosericea* and *Acacia nilotica* drying more quickly than soil close to *Azadirachta indica* windbreaks.

*Differences in water extraction among species*

The observations of soil water content in the vicinity of windbreak trees presented here demonstrate that there are differences in potential competitiveness for water among tree species used in agroforestry in the Sahel. *Azadirachta indica* appears to be less competitive than either *Acacia nilotica* or *Acacia holosericea* because its presence does not diminish soil water contents in the root zone of the crop to the same extent. The reason for this is probably that it uses less water, as was demonstrated by the comparison among species of transpiration rates measured with the heat-pulse technique, and so extracts less water from lateral roots that extend into the root zone of the crop. Infiltration of water beyond the surface layers of the soil appears to be reduced between the trunks of *Acacia holosericea* and *Acacia nilotica* trees and some point between 2.5 and 5.0 m into the millet crop. The most probable explanation of this is that extraction of water by lateral roots of these species prevents drainage of water into the deeper layers of the profile until a rainstorm or series of rainstorms occur that are sufficiently large to wet the soil beyond the surface layers. Other possible explanations are less plausible, but include higher interception of rainfall by the foliage of the *Azadirachta indica* windbreaks, and therefore higher stem flow, or differences among species in their influence on the infiltration capacities of soils. Further studies of water balances in the vicinity of windbreaks of these species would clarify the causes of differences among them in the moisture status of nearby soil.

### **2.3.7** *Influence of water uptake by trees on crop yields*

In years or periods of low rainfall, the quantity of water available to crops is likely to be less near windbreaks of the two *Acacia* species than near *Azadirachta indica* windbreaks. The impact of this reduction in the availability of water on growth and yields of the crop depends on the degree and duration of consequent water stress and on the area of the crop affected. More severe stress over wider areas will cause higher yield losses because moisture stress reduces opening of stomata and, therefore, the amount of carbon fixed during photosynthesis by the crop. Crop yields at the site are not reported here, so it is not possible to assess the effect on crop production of competition for water by the windbreak trees, although it would be very difficult to distinguish the influence of competition for moisture on crop yields from the effects of other interactions between the trees and the crop. However, the data presented here show that soil moisture content can be reduced to a distance of between 2.5 and 5 m from the base of competitive trees such as *Acacia holosericea* or *Acacia nilotica* managed as hedge windbreaks. There was 30 m of cropland between windbreaks at the site and considering both edges of the cropped area, it is therefore possible that competition for water from *Acacia nilotica* and *Acacia holosericea* can influence the crop in up to approximately 30 % of the field in the hedge windbreak system in which this study was made. Competition for water from *Azadirachta indica* windbreaks would have much less effect on the crop, so that, during dry periods or years, *Acacia holosericea* and *Acacia nilotica* would cause higher losses of crop yield as a result of competition for water than *Azadirachta indica*.

Other studies of below-ground competition between windbreak trees and crops have established the influence of competition for water on crop yields by pruning the roots of the trees and correlating improvements in yields with increases in soil moisture contents in comparison to plots where root pruning was not used (Singh and Dayal, 1975; Lyles *et al.*, 1984; Onyewotu *et al.*, 1994). For example, Onyewotu *et al.* (1994) found that pruning the roots of 12 m-tall windbreaks of *Eucalyptus camaldulensis* Denh. in northern Nigeria at 3 m from the trees resulted in an increase in millet yields from 14 to 1225 kg $ha^{-1}$ up to 18 m from the trees. Brenner (1991) applied a similar treatment to 6 m-tall windbreaks of *Azadirachta indica* in south-western Niger and found that below-ground competition reduced grain yields of millet up to a distance of 10 m from the trees, but by only 17 %. The discrepancy between these two studies occurred because the eucalypt is clearly very competitive for water while, as demonstrated by data presented here, the potential competitiveness of *Azadirachta indica* trees for water is low. Thus, the identification of tree species used in agroforestry in the Sahel as strongly or weakly competitive will provide valuable information to those with the responsibility of selecting species for establishment in new windbreak plantings. At locations where competition for water is thought to be important, therefore, the likelihood that the windbreaks will be acceptable to local farmers can be improved by ensuring that only weakly competitive tree species are planted, so that the benefits to crop yields provided by shelter are not negated by competition for water.

## 2.4 Conclusions

*Azadirachta indica* is less competitive for water than either *Acacia holosericea* or *Acacia nilotica* because it transpires less water and extracts less water from the root zone of adjacent crops. Specific, quantitative aspects of these findings apply only to the hedge windbreak system on which this study was done, but the general conclusions drawn from the results concerning the management of competition in agroforestry in the semi-arid tropics are widely applicable.

This study demonstrated that differences in the potential competitiveness for water of tree species used in agroforestry can be assessed by examining the influence of water use by the trees on the availability of water to nearby crops. Trees that deplete water at lower rates from zones of the soil exploited by crops are less competitive. Thus, at locations where planners fear that competition between trees and crops will cause unacceptable loss of crop yields, they should plant only weakly competitive species in windbreaks or other arrangements suitable for agroforestry in the semi-arid tropics. Planners consequently require information on the relative competitiveness of a wide variety of tree species suitable for use in semi-arid areas, if they are to ensure that agroforestry in these regions is able to meet the demand of local people for a diverse range of tree products. This information could be collected by repeating the measurements made during this study on many more tree species at different locations. However, if demand for water by windbreak trees is correlated with stomatal conductance and leaf area, the required information might be drawn instead from simpler, less expensive surveys of the relative magnitudes of stomatal conductances and leaf areas typical of species suitable for use in agroforestry in the Sahel. This approach should be valid because windbreak trees are closely coupled to the atmosphere, as demonstrated by Equation 2.10 and discussed in Chapter 6, and so have good stomatal control of transpiration.

Information concerning the relative competitiveness of tree species would also be useful to farmers and development agents trying to devise management strategies for windbreaks in the Sahel. Where species are known to compete strongly with crops for water, interventions designed to reduce demand for water by the trees should be considered. Pruning of windbreaks appears to reduce water use and so pruning strategies could be employed to reduce demand for water by the trees at critical times. Pruning of windbreak canopies to reduce competition has also been advocated by van den Beldt (1990), but knowledge of the relative competitiveness of species should be used to ensure that the severity of pruning imposed on the trees matches the likely impact of the trees on crop production. Windbreaks should not be pruned more severely than necessary because pruning will also reduce the efficacy of the windbreak as a barrier to damaging winds. Thus, tests are required to determine optimum strategies for pruning windbreaks that minimise their demand for water but maximise the extent of the area they shelter.

The ability to generalise results on the basis of the mechanisms governing environmental processes is an important advantage of process-based studies of competition over empirical studies of yield reductions in agroforestry. It is difficult to assess the competitiveness of windbreak trees by examining changes in crop yields because competition is then only one of several interacting processes that influence yield in crop fields sheltered by windbreaks. Thus, it is most straightforward to use the approach employed in this study and compare the relative competitiveness of tree species in agroforestry by examining differences in rates at which each depletes resources from the environment. This information will be valued by land-use planners, farmers and development agents because it will help them to select tree species for use in agroforestry in the semi-arid tropics on a rational basis.

# Chapter 3

# Sources of Water Transpired by Trees and Crops in Sahelian Windbreak Systems

## 3.1 Introduction

When windbreaks are planted across the prevailing wind direction, wind speeds are reduced in a sheltered zone to the lee of the trees (McNaughton, 1988; Brenner, 1991). Shelter thus protects soils from wind erosion (Onyewotu, 1983; Michels, 1994) and, because turbulent transport is less efficient behind windbreaks than above open fields, shelter also improves the microclimate for crop growth (McNaughton, 1983, 1988), causing higher air temperatures and lower vapour pressure deficits in the sheltered zone (McNaughton, 1988). Less efficient turbulent transport results in less dry air advection to sheltered crops (McNaughton, 1983) and, consequently, less advective enhancement of evapotranspiration from sheltered crops than from crops fully exposed to atmospheric turbulence (Miller *et al.*, 1973; McNaughton, 1983). Higher crop yields have often been observed behind windbreaks in the Sahel as a result of these modifications to crop microclimate (Ujah and Adeoye, 1984; Long, 1989; van den Beldt, 1990; Brenner, 1991), although there are locations where total crop production is not enhanced because competition for resources between trees and crops can exacerbate stresses in crop plants and reduce yields near the trees (Kessler and Breman, 1991; Brenner *et al.*, 1993; Onyewotu *et al.*, 1994). Competition for resources occurs where plants of several species are growing together in a mixed stand and utilisation of resources by one species reduces their availability to other species (Grime, 1979; Connell, 1990). Where windbreaks have been established, consequently, competition for water from trees can reduce yields of adjacent crops because extraction of water by tree roots causes the soil to dry more quickly, thus lengthening and increasing the severity of water stress in the crop during dry spells.

In the Majjia Valley in central Niger, where a network of windbreaks protects over 3000 ha of cropland (DANIDA, 1991), Long (1989) and others (see van den Beldt, 1990) found that grain yields of pearl millet (*Pennisetum glaucum* (L.) R. Br.) were 20-25 % higher in fields sheltered by windbreaks than in unsheltered fields, even when land occupied up by the trees was accounted for. In contrast, Brenner *et al.* (1993) showed that the enhancement of millet yields behind windbreaks at Sadoré, in south-western Niger, only just compensated for production lost from land occupied by the trees. The windbreaks at both sites are formed by double rows of mature *Azadirachta indica* A. Juss. trees, but there is a large difference between the sites in the depth of groundwater below the soil surface. The water table in the Majjia Valley occurs at a depth of 6-10 m, while, at Sadoré, there is a hard layer of laterite at between 4 and 6 m and the water table is found at approximately 35 m. The proximity of groundwater to the soil surface in the Majjia Valley led Sumberg and Burke (1991) to caution against extrapolating expectations concerning the productivity of crops behind windbreaks from the Majjia Valley to other locations in the Sahel and led van den Beldt (1990) to suggest the hypothesis that differences between locations in crop productivity behind windbreaks may arise because competition for water between trees and crops is less severe at locations where groundwater is accessible to tree roots. Production of millet behind windbreaks may, therefore, be higher in the Majjia Valley than at Sadoré because competition for water between the windbreaks and crop is less severe in the Majjia Valley because trees there can utilise groundwater.

In order to test this hypothesis, a method of distinguishing uptake of water by plants from different sources was used to determine whether windbreak trees in the Majjia Valley are able to use groundwater while trees at Sadoré must use water from the same depths in the soil profile as the adjacent millet crop. The method uses naturally-occurring variations in the ratios of stable isotopes of oxygen ($^{18}O/^{16}O$) or hydrogen ($^{2}H/H$) as markers for water that may be available to vegetation for uptake. Isotopic ratios for groundwater represent long-term, weighted averages of the isotopic composition of rainwater that has drained down to the water table (Flanagan and Ehleringer, 1991; Joseph *et al.*, 1992) or, in the case of fossil groundwaters, isotopic ratios depend on hydrological processes of earlier time periods (Dawson and Ehleringer, 1991). Isotopic ratios for water in upper horizons of the soil change much more rapidly. They depend on the isotopic composition of recent precipitation, which itself varies with the composition, temperature and distance travelled by the air mass from which the rainfall is derived (Datta *et al.*, 1991; Joseph *et al.*, 1992), and on evaporation from the soil, because isotopic fractionation occurs during evaporation, leaving water in the soil enriched with heavier isotopes (Allison *et al.*, 1983; Barnes and Allison, 1983). Differences often occur, consequently, in isotopic ratios of groundwater and rainwater or soil water. Because there is no isotopic fractionation of water during the movement of water into plant roots (Dawson and Ehleringer, 1991; Walker and Richardson, 1991; Thorburn *et al.*, 1993) or through suberised stems (Dawson and Ehleringer, 1993; Thorburn *et al.*, 1993), the source of water taken up by plants can therefore be identified by comparing isotopic ratios for water from all possible sources and sap in the xylem vessels of plant stems (Brunel *et al.*, 1991; Dawson and Ehleringer, 1991; Thorburn *et al.*, 1993; Brunel *et al.*, 1995).

The technique has been used previously by others for ecological investigations of water uptake by plants. White *et al.* (1985) used ratios for hydrogen isotopes in water to compare use of groundwater and recent rainfall by forest trees in the eastern United States. Their analysis showed that trees with access to groundwater used rainwater in the days following rainfall, but used increasing proportions of groundwater as the rainwater in the soil was depleted. They quantified the fractional contribution of groundwater and rainwater to plant sap by determining the weighting for isotopic ratios of groundwater and rainwater necessary to give a mean value equal to the isotopic ratio for the tree sap. Dawson and Ehleringer (1991) used stable isotopes in water to demonstrate that mature trees growing on a stream bank utilised deep groundwater rather than stream water and Ehleringer *et al.* (1991) and Flanagan *et al.* (1992) used the technique to compare utilisation of summer rainfall and groundwater or stored soil moisture among species with contrasting growth habits in plant communities in the south-western United States. Brunel *et al.* (1991), Walker and Richardson (1991) and Brunel *et al.* (1995) compared isotopic ratios of plant sap and water in the soil profile and identified soil layers from which plants were taking up water. Stable isotope techniques have not been used to contrast the utilisation of water by trees and crops in agroforestry until now.

## 3.2 Materials and methods

### **3.2.1** *Site descriptions*

Samples used in the study were collected from windbreaks of *A. indica* and adjacent fields of pearl millet at Sadoré and in the Majjia Valley. The windbreaks at Sadoré (13°14'N, 2°16'E) are located on the research farm of the ICRISAT Sahelian Centre, about 45 km south of Niamey, the capital of Niger. The Majjia Valley is found some 400 km to the north-east, approximately 20 km south of the town of Bouza (14°25'N, 6°03'E). Rainfall at both locations is confined to a single, short rainy season, normally lasting from June to September, although the Majjia Valley is situated in a drier region than Sadoré, with mean annual rainfall of 379 mm at Bouza compared to 545 mm at Niamey (Sivakumar *et al.*, 1993). The soil at the Sadoré site is a sandy alfisol (Psammentic Paleustalf) which overlies a hard layer of laterite at a depth of 4.6 m. At the Majjia Valley site, the soil is a loamy inceptisol (Fluventic Ustropept) and there is no lateritic layer.

The windbreaks at both locations are formed by double rows of alternately planted *A. indica* trees, approximately 8 m in height. In the Majjia Valley, samples were taken from a windbreak planted in 1977 growing adjacent to a well north of the village of Wassourou. Samples were collected at Sadoré from a windbreak planted in 1984 that separates fields 3 and 4C from fields 3 and 4D of the ICRISAT Sahelian Centre.

**3.2.2** *Sampling procedures*

Complete assessment of the sources of water taken up by plants at the two sites required that samples of soil, groundwater, rainwater, *A. indica* twigs and, when present, millet were collected from each location. Samples of rainwater were collected following rainfall events and soil, groundwater and plant samples were collected on five occasions at each site between DOY 240, 1992, and DOY 274, 1993. There was an interval of a few days between sampling at the two sites on each occasion and so, to facilitate comparisons between sites, sampling dates are referred to by the seasons of the year in which they fell. These were: (1) the rainy season, 1992; (2) the early dry season, 1992; (3) the late dry season, 1993; (4) the middle of the rainy season, 1993; and (5) the late rainy season, 1993. Actual dates of sampling at each location are summarised in Table 3.1.

On each sampling date, samples of twigs were cut with secateurs from nine randomly-selected *A. indica* trees along a length of windbreak of approximately 100 m and, as recommended by Dawson and Ehleringer (1993), only mature, suberised twigs were collected because isotopic fractionation of xylem sap can result from evaporation through immature bark. When the millet crop was present, as on three sampling dates at each site (Table 3.1), samples of millet stem were collected from nine plants along a transect running

**Table 3.1:** Dates on which samples were collected for analysis of isotopic ratios in the Majjia Valley (MV) and at Sadoré (SD) during 1992 and 1993. Also shown is the season in which each sampling day occurred and the status of the millet crop on each occasion.

| Year | Season | Site | Date of sampling (DOY) | Millet growth stage |
|---|---|---|---|---|
| 1992 | Rainy season | MV | 240 | Grain filling |
| | | SD | 244 | Grain filling |
| | Early dry season | MV | 323 | Not present |
| | | SD | 328 | Not present |
| 1993 | Late dry season | MV | 131 | Not present |
| | | SD | 120 | Not present |
| | Mid-rainy season | MV | 208 | 3 tillers |
| | | SD | 214 | 2 tillers |
| | Late rainy season | MV | 266 | Grain filling |
| | | SD | 274 | Grain filling |

**Table 3.2:** Depths at which soil samples were collected on each sampling date in the Majjia Valley (MV) and at Sadoré (SD).

| | Sampling date (DOY) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1992 | | | | 1993 | | | | | |
| | 240 | 244 | 323 | 328 | 131 | 120 | 208 | 214 | 266 | 274 |
| Depth (m) | MV | SD | MV | SD | MV | SD | MV | SD | MV | SD |
| 0 | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| 0.1 | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| 0.25 | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 0.5 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 1.0 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 1.5 | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 2.0 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 3.0 | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ |

parallel to the windbreak, 30 m from the trees. Because millet stems are non-suberised, efforts were made to gather pieces of stem from which transpiration through stem walls was likely to be minimal and so, in 1992, pieces of millet stem were taken from within the sheath of the top-most leaf of plants and, in 1993, segments of stem situated just above the soil surface were sampled at least 2 h after being wrapped in plastic film. Samples of twigs and millet stem were about 8 cm long.

Soil samples were collected at three positions within the windbreak and, when the crop was present, at three points along the transect within the millet. Samples were taken from the soil surface and from depths of 0.1, 0.25, 0.5, 1.0, 1.5, 2.0 and 3.0 m using a soil auger, although, as shown in Table 3.2, samples were not collected from all depths on all dates.

Samples of groundwater were collected in the Majjia Valley from a well located less than 100 m from the windbreak sampled in the study. At Sadoré, samples of groundwater were taken from two boreholes located within about 400 m of the windbreak and from a village well about 2 km west of the site. The depth of groundwater was measured at the wells at both locations using a measuring tape.

Rainwater was collected following all rainfall events at both locations during 1993, although two rains were missed in the Majjia Valley. At Sadoré, rainwater samples were taken from a raingauge located approximately 300 m from the windbreak, while, in the Majjia Valley, samples were collected from a raingauge at the village of Garadoumé, about 5 km from the windbreak site.

All plant and water samples were placed in plastic test tubes immediately after collection and sealed with threaded caps containing o-rings (Sarstedt Ltd., Leicester, UK.) to prevent water loss. Soil samples were sealed inside two plastic bags. All samples were stored in an insulated cool-box (except the rainfall samples from the Majjia Valley) until frozen at -18 °C in a freezer, where they remained until transported to Edinburgh University, where they were again frozen until analysed.

### **3.2.3** *Analysis of samples*

Isotopic composition of water in the various samples collected in this study was assessed by measuring isotopic ratios for oxygen ($^{18}O/^{16}O$). Measurements were made for all types of samples using the new direct equilibration method described by Scrimgeour (1995) rather than conventional methods which, for plant and soil samples, require extraction and recovery of all water contained in the sample matrix, usually by azeotropic distillation (Thorburn *et al.*, 1993). Distillation is not required in Scrimgeour's method because measurements are made on $CO_2$ that has equilibrated with the water in samples within a closed volume under controlled conditions for which fractionation of $^{18}O$ between $H_2O$ and $CO_2$ at equilibrium is known. Results of analyses of soil and plant samples made using this method have been shown by Scrimgeour (1995) generally to agree to within measured errors with analyses made using azeotropic distillation.

Isotopic ratios for all samples analysed were measured using an isotope ratio mass spectrometer (Tracermass, Europa Scientific Ltd., Crewe, UK.) at the Scottish Crops Research Institute, Dundee. All nine twig or millet samples were analysed for each sampling date in 1992, but determinations were made on a random selection of four of the nine twig or millet samples collected on each date in 1993. Gravimetric moisture contents of the soil samples were determined during the course of the analyses.

### **3.2.4** *Data analysis*

Ratios of stable isotopes are normally expressed relative to a standard using delta (δ) notation, with $\delta^{18}O$ given by

$$\delta^{18}O = \left( \frac{R_S}{R_{SMOW}} - 1 \right) 1000, \tag{3.1}$$

where $R_S$ and $R_{SMOW}$ are the $^{18}O/^{16}O$ ratios for the sample and Standard Mean Ocean Water (SMOW), respectively (Ehleringer and Dawson, 1992). Units of $\delta^{18}O$ are per mil (‰). Positive values of $\delta^{18}O$ indicate enrichment of $^{18}O$ relative to SMOW and negative values represent depletion (Preston, 1992). The significance of differences in $\delta^{18}O$ values among samples was evaluated using Student's t-test.

### 3.3 Results and discussion

### 3.3.1 *$\delta^{18}O$ values for groundwater and rainwater*

Values of $\delta^{18}O$ for the groundwater and rainwater samples collected in 1993 are shown in Fig. 3.1a for the Majjia Valley and in Fig. 3.1b for Sadoré. Isotopic ratios for groundwater varied only slightly over the year at both locations, as found by Flanagan *et al.* (1992) for groundwater at a site in the south-western United States. The mean $\delta^{18}O$ value for groundwater in 1993 was -4.35±0.23 ‰ in the Majjia Valley and -4.69±0.15 ‰ at Sadoré, in close agreement with values given by Joseph *et al.* (1992) for groundwater at nearby sites. Values of $\delta^{18}O$ for rainwater were much more variable and changed abruptly at both locations in the middle of the rainy season from values near 0 ‰ to values near -5 ‰. The cause of this shift in $\delta^{18}O$ values for rainfall was perhaps the passage of the inter-tropical convergence zone (ITCZ) across the region because the isotopic characteristics of rainwater are known to depend on the origin and composition of the air mass from which rainfall condenses (Datta *et al.*, 1991; Joseph *et al.*, 1992) and the ITCZ separates dry, desert air from moist, tropical air and can be expected to cross the latitudes of the locations studied at a time roughly coincident with the observed shift in $\delta^{18}O$ values.

### 3.3.2 *$\delta^{18}O$ values for soil water*

Figures 3.2 to 3.6 show profiles of $\delta^{18}O$ values for water in the surface layers of the soil on each sampling date at Sadoré and the Majjia Valley. The gradients with depth in $\delta^{18}O$ values for soil water evident in each case probably resulted from the combined effects of variations in the isotopic composition of recent rainfall (Ehleringer and Dawson, 1992), isotopic enrichment of soil water by evaporation (Allison *et al.*, 1983; Barnes and Allison, 1983) and mixing of rainwater and soil water previously enriched by evaporation (Brunel *et al.*, 1991). An important consequence of these processes is that $\delta^{18}O$ values for recent rainwater are not necessarily indicative of the isotopic composition of water available to plants from near the soil surface. Uptake of water from the surface layers of the soil cannot, therefore, be distinguished from uptake of water stored more deeply in the soil by comparing the isotopic composition of plant sap and rainwater at sites where there are gradients in $\delta^{18}O$ values for soil water. Other workers (White *et al.*, 1985; Dawson and Ehleringer, 1991; Ehleringer *et al.*, 1991; Flanagan *et al.*, 1992) have previously made such comparisons at other locations, but they ignored the possibility that isotopic ratios for rainwater change in the interval between a rainfall event and arrival of the water at the root

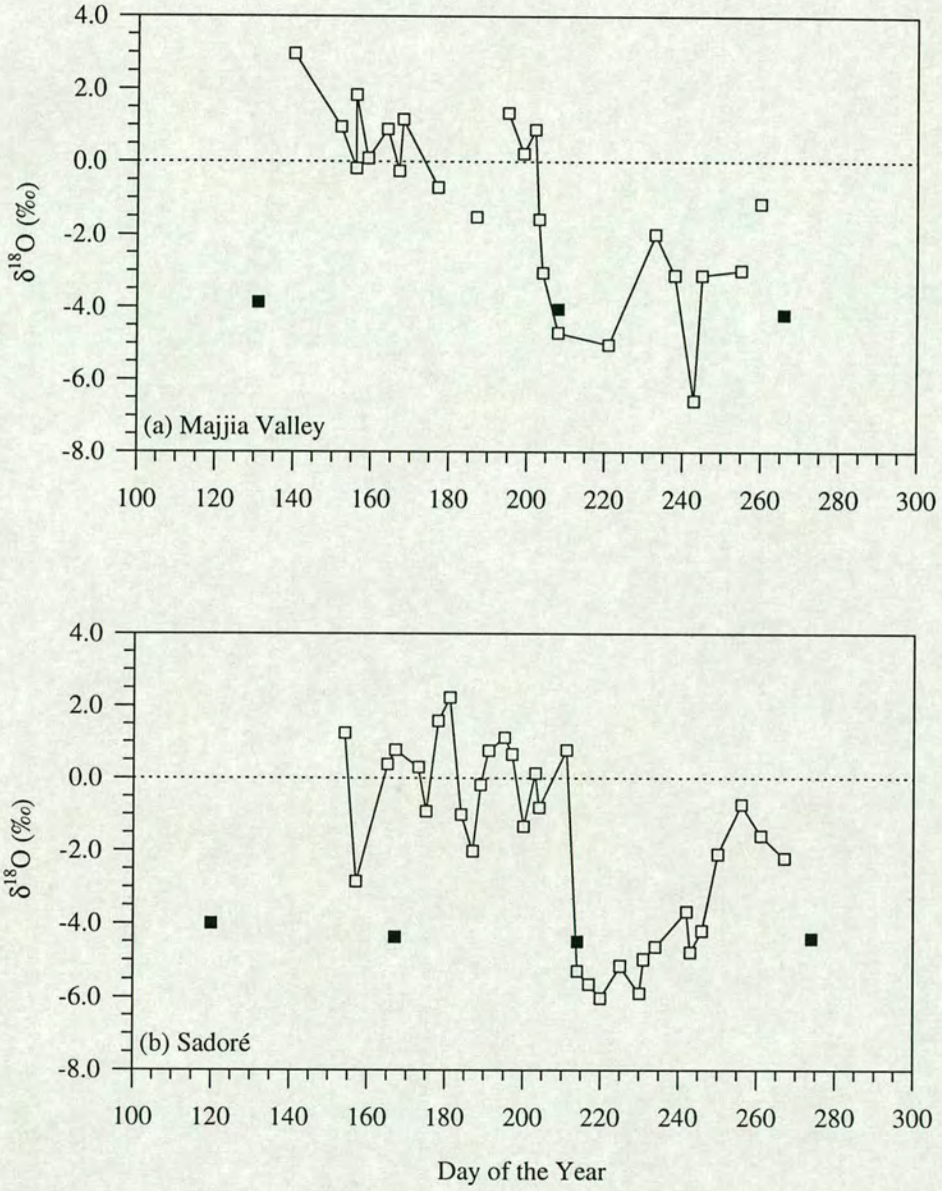


**Figure 3.1:** Values of $\delta^{18}O$ for rainfall ( □—□ ) and groundwater ( ■ ) sampled in 1993 at (a) the Majjia Valley and (b) Sadoré.

surface prior to uptake. Thus, in order to determine the sources of water used by plants, it is important that isotopic ratios for plant sap are compared with values for soil water and groundwater, rather than just rainwater and groundwater (Brunel *et al.*, 1991, 1995).

### **3.3.3** *Sources of transpired water*

#### *1992 rainy season*

Figures 3.2a and 3.2b show values of $\delta^{18}$O for tree sap, millet sap, groundwater and soil water between the surface and 3 m for the dates samples were collected in the 1992 rainy season in the Majjia Valley and at Sadoré. Values of $\delta^{18}$O for millet and tree sap were not significantly different ($P<0.05$) at the Majjia Valley site on this date (Fig. 3.2a), but both were significantly higher ($P<0.005$) than the value for groundwater and both coincided with $\delta^{18}$O values for water from near the soil surface. Water used by the plants was not taken up precisely from depths in the soil with matching $\delta^{18}$O values because, as discussed by Ehleringer and Dawson (1992), the isotopic composition of plant sap is an integrated measure of water uptake from the various depths in the soil which the plant is exploiting. Values of $\delta^{18}$O for plant sap are determined, consequently, by the mean isotopic ratios for water from all sources utilised by the plants, weighted by the proportional contribution of each source. Figure 3.2a should be interpreted, therefore, as showing that when sampling occurred in the Majjia Valley in the 1992 rainy season, both the trees and crop were obtaining the bulk of their water from the top 1 m of the soil profile. Soil moisture data for this date (Fig. 3.2a (inset)) reinforce this conclusion because there was plenty of water available for uptake at the top of the soil profile as a result of 44 mm of rain which had fallen at the site during the night before the samples were collected.

By coincidence, a similar situation existed when samples were collected at Sadoré in the 1992 rainy season because 45 mm of rain had fallen the previous day, making soil near the surface moist relative to deeper layers (Fig. 3.2b (inset)). Values of $\delta^{18}$O for tree and millet sap both coincided with values for soil water from the top 1 m of the soil at Sadoré on this occasion (Fig. 3.2b), indicating uptake of water from near the surface by both windbreak and crop. A contribution to tree transpiration by groundwater is not definitively disproved by the data in Fig 3.2b, but given that the soil surface was very moist and the water table was at 34.7 m, it is probable that the trees at Sadoré were using only soil water on this occasion. The data from samples collected at both locations in the 1992 rainy season therefore demonstrate that the windbreak trees and millet at both Sadoré and the Majjia Valley were able to utilise water from the top of the soil profile when the soil there was moist.

#### *Early dry season, 1992*

The soil had become much drier at both sites by the next pair of sampling dates (Figs. 3.3a and 3.3b (inset)), which were early in the 1992/93 dry season, after two months without rain. In the Majjia Valley on this occasion, the $\delta^{18}$O value for tree sap was significantly higher ($P<0.025$) than the value for groundwater, but was intermediate with

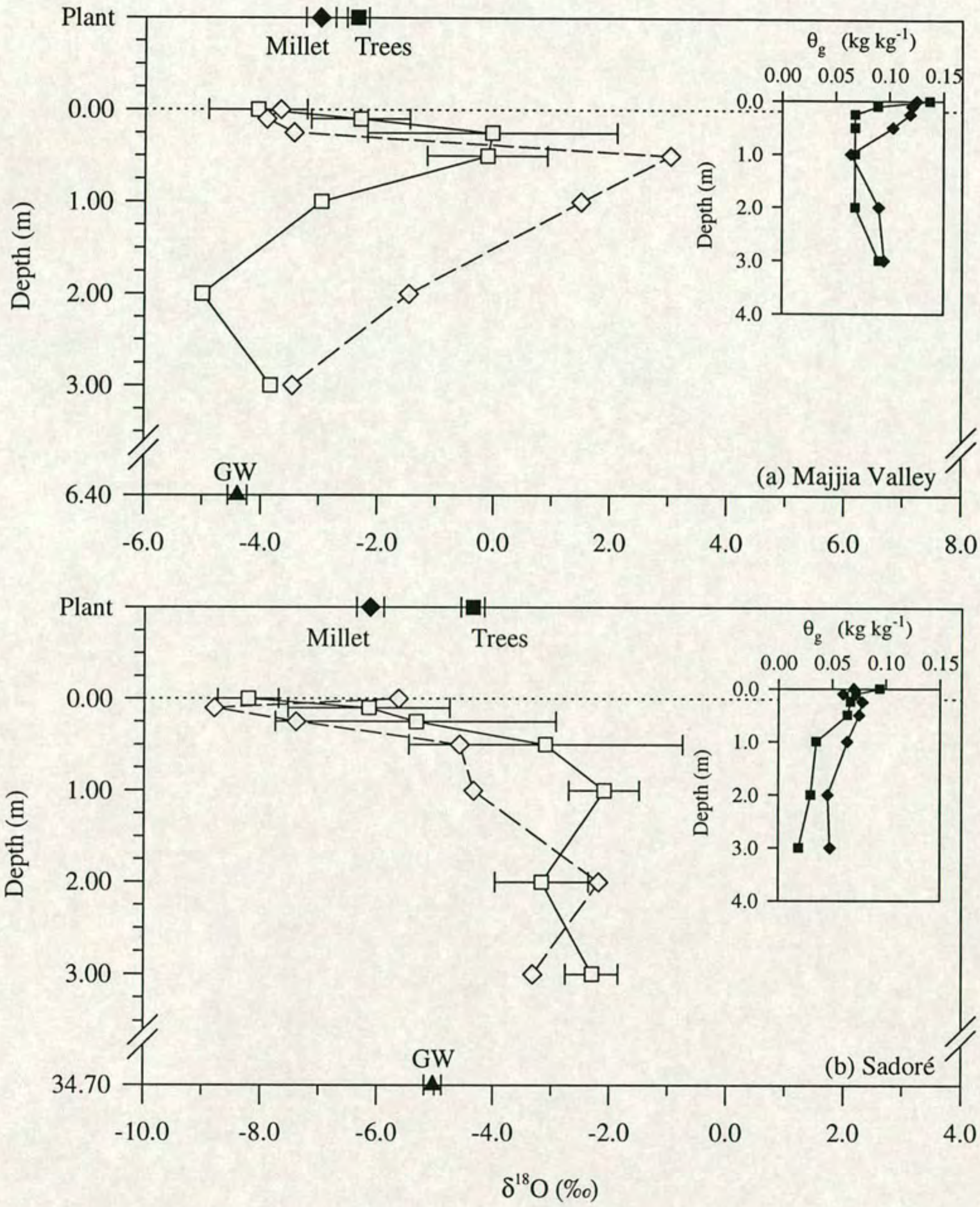


**Figure 3.2:** Profiles of $\delta^{18}O$ values for soil water measured in the 1992 rainy season beneath *Azadirachta indica* windbreaks (□——□) and adjacent millet crops (◇— —◇) at (a) the Majjia Valley (DOY 240, 1992) and (b) Sadoré (DOY 244, 1992). Values of $\delta^{18}O$ for groundwater (GW) (▲), tree sap (■) and millet sap (◆) are shown for comparison and, inset, the gravimetric moisture content ($\theta_g$) of soil beneath the windbreaks (■——■) and the crop (◆——◆) are shown for each location for reference. Error bars show ±1 s.e.

respect to the values for groundwater and soil water at a depth of 2 m (Fig. 3.3a). As moisture was depleted from the upper layers of the soil at the Majjia Valley site, therefore, the trees were able to utilise water from deeper soil layers. Because $\delta^{18}O$ values for plant sap are averages for water from contributing sources, the $\delta^{18}O$ value for tree sap in this instance most likely resulted from utilisation of water from a range of soil depths including levels below 2 m and, possibly, the level of the water table at 6.8 m.

In contrast, at Sadoré early in the dry season, the $\delta^{18}O$ value for tree sap coincided with values from the top 2 m of the soil (Fig. 3.3b) and was significantly different ($P<0.01$) from the value for groundwater at the site. Even when soil near the surface had become quite dry, therefore, the trees at Sadoré were unable to draw groundwater up from a depth of 35 m, indicating that roots of the trees had not penetrated to such depths. Deans *et al.* (1994) found live roots of *A. indica* at depths of 30 m in a sandy soil in northern Senegal, but because the trees at Sadoré did not begin to exploit groundwater when the soil near the surface had become dry, it is evident that they did not have similarly deep root systems.

*Late dry season, 1993*

Later in the same dry season, after a further six months without rain, the soils at both sites had $\delta^{18}O$ profiles typical of soils from which evaporation has been considerable, with strong enrichment of heavier isotopes near the soil surface (Figs. 3.4a and 3.4b) as a result of evaporative fractionation (Allison *et al.*, 1983; Barnes and Allison, 1983). Below this level, $\delta^{18}O$ values for soil water in the Majjia Valley decreased approximately exponentially with depth to a roughly constant value that coincided with the value for groundwater. The $\delta^{18}O$ values for tree sap, groundwater and soil water from below 1.5 m were, consequently, all similar (Fig. 3.4a), so that it is only possible to resolve that, on this occasion, the trees were using water from below 1.5 m, probably including groundwater.

At Sadoré at the end of the dry season, the trees appear to have continued to use water from the top 2 m of the soil profile because $\delta^{18}O$ values for soil water and tree sap coincided again (Fig. 3.4b). A contribution to tree transpiration by groundwater is discounted because of the results from the early dry season, but it is possible that water from below 2 m, which was not sampled, was utilised by the trees if $\delta^{18}O$ values for soil water from those levels were similar to values observed at 2 m and above.

*1993 rainy season*

The results obtained from sampling dates in both the mid- and late 1993 rainy season were similar, but there were differences between locations. At the Majjia Valley site on both these occasions, values of $\delta^{18}O$ for millet and *A. indica* sap were

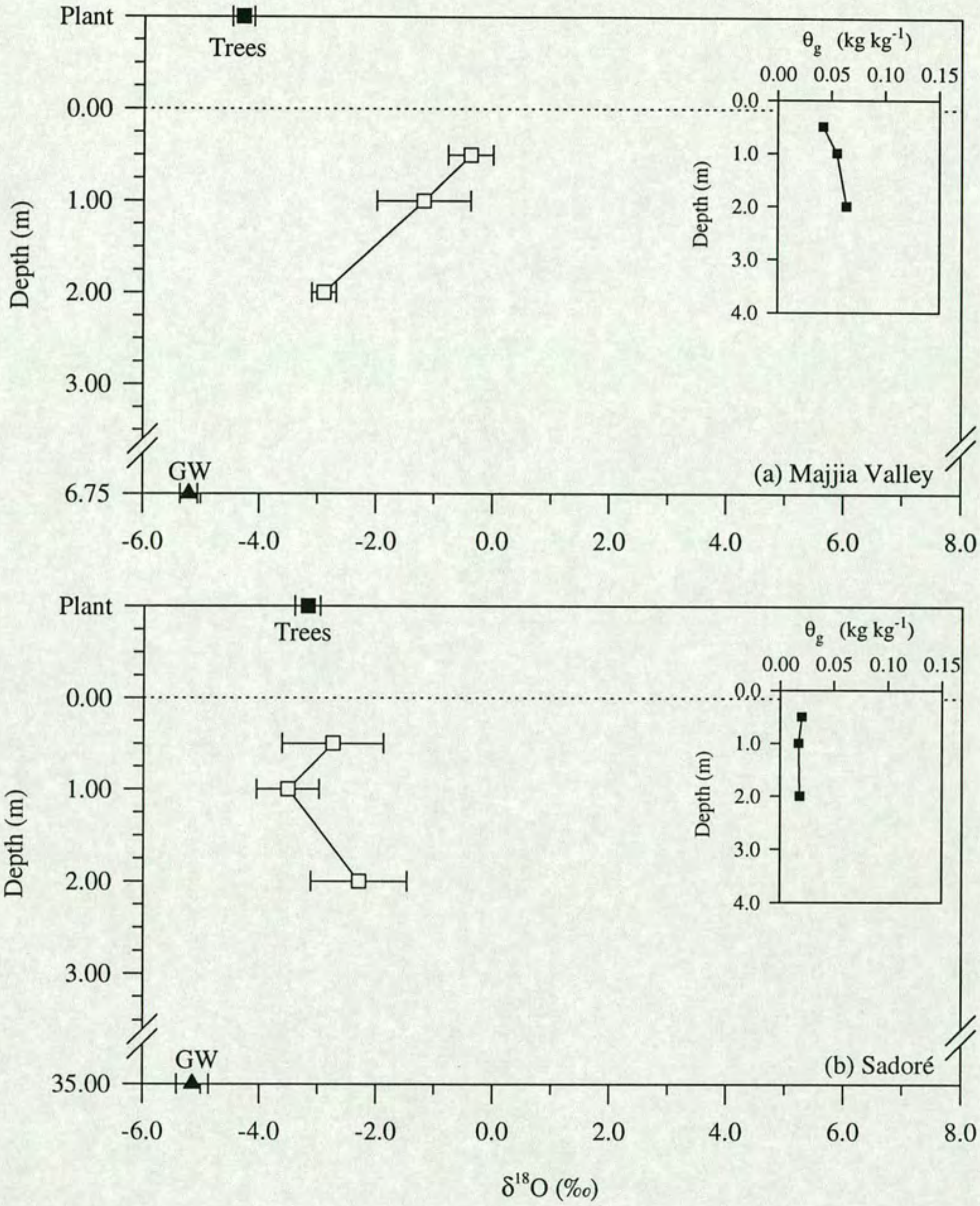


**Figure 3.3:** Profiles of $\delta^{18}O$ values for soil water measured in the early 1992/93 dry season beneath *Azadirachta indica* windbreaks (□——□) at (a) the Majjia Valley (DOY 323, 1992) and (b) Sadoré (DOY 328, 1992). Values of $\delta^{18}O$ for groundwater (GW) (▲) and tree sap (■) are shown for comparison and, inset, the gravimetric moisture content ($\theta_g$) of soil beneath the windbreaks (■——■) is shown for each location for reference. Error bars show ±1 s.e.

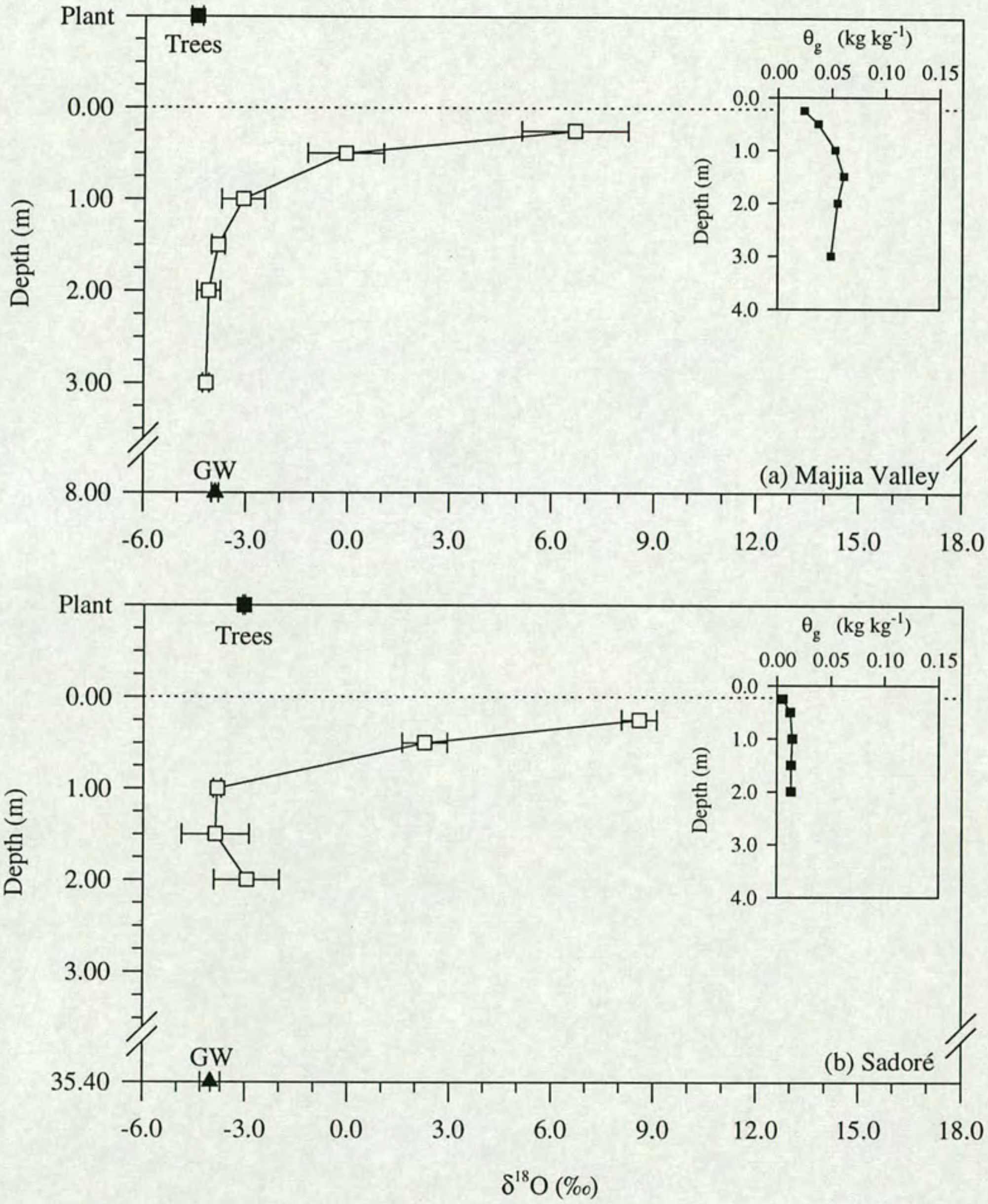


**Figure 3.4:** Profiles of δ$^{18}$O values for soil water measured in the late 1992/93 dry season beneath *Azadirachta indica* windbreaks (□——□) at (a) the Majjia Valley (DOY 131, 1992) and (b) Sadoré (DOY 120, 1992). Values of δ$^{18}$O for groundwater (GW) (▲) and tree sap (■) are shown for comparison and, inset, the gravimetric moisture content (θ$_g$) of soil beneath the windbreaks (■——■) is shown for each location for reference. Error bars show ±1 s.e.

significantly different ($P<0.05$) (Figs. 3.5a and 3.6a): the values for millet sap coincided with values for soil water from the top 1 m of the soil, whereas the $\delta^{18}O$ values for tree sap coincided with values for soil water from below 2 m and were not significantly different ($P<0.05$) from values for groundwater on either occasion. The soil near the surface was much drier on these sampling dates (Figs. 3.5a (inset) and 3.6a (inset)) than it had been when sampled in the 1992 rainy season (Fig. 3.2a (inset)) and so it appears that when water was not plentiful near the soil surface, windbreak trees in the Majjia Valley were able to extract water from soil below 2 m, probably obtaining some water from at or near the water table. Extraction of soil water by millet was confined to the rooting zone of millet, which extends only to a depth of approximately 1.5 m (Payne *et al.*, 1990), and so, consequently, competition for water from windbreak trees is unlikely to have much effect on millet growth in the Majjia Valley.

On both sampling dates in the 1993 rainy season at Sadoré, the $\delta^{18}O$ values for millet and tree sap were not significantly different ($P<0.05$) and both coincided with values from the top 3 m of the soil (Figs. 3.5b and 3.6b). On both occasions, mean $\delta^{18}O$ values for the trees were lower than the values for soil water from beneath the trees. This could indicate utilisation of groundwater, but the results from the early 1992/93 dry season showed that the roots of the trees had not reached the water table. The low $\delta^{18}O$ for the trees may, therefore, demonstrate exploitation of water from deep soil layers for which $\delta^{18}O$ values are unknown, or they may show that the trees obtained a portion of their water from lateral roots which extended into the rooting zone of the crop, where $\delta^{18}O$ values for soil water tended to be lower (Figs. 3.5b and 3.6b). The latter explanation is more likely because soil under the trees below a depth of 2 m was very dry compared to soil under the crop (Figs. 3.5b and 3.6b (inset)). On the basis of this interpretation of the data, it appears that, when sampled in the middle of the 1993 rainy season, the trees at Sadoré were, like the millet, obtaining a portion of their water from the top 0.5 m of the soil beneath the crop (Fig. 3.5b). Similarly, it appears that the trees were obtaining water from depths beneath the crop of between 1 and 2 m when sampled in the late rainy season, 1993 (Fig. 3.6b). Thus, it is apparent that competition for water between the trees and crop occurs at Sadoré when moisture is not abundant in the the surface layers of the soil.

### **3.3.4** *Proportioning water uptake from different sources*

White *et al.* (1985) and Ehleringer *et al.* (1991) suggested that the proportion of water taken up from two sources can be quantified by interpolating between the isotopic ratios of each source. The proportion ($P_s$) of water taken up from a source $s$, where $s$ is either a lower (eg. groundwater) or higher (eg. soil water) source in the soil profile, is then given by

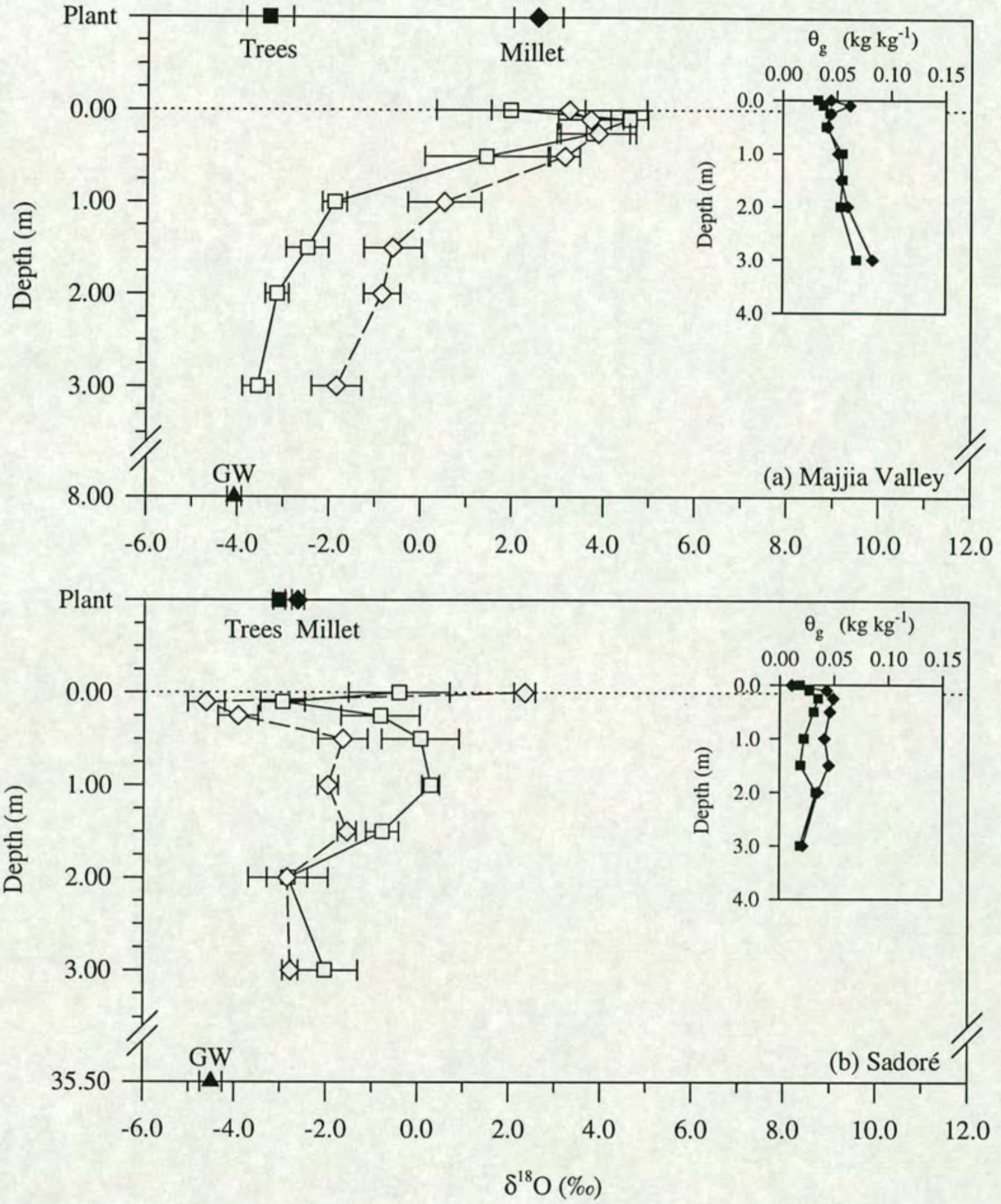


**Figure 3.5:** Profiles of $\delta^{18}$O values for soil water measured in the middle of the 1993 rainy season beneath *Azadirachta indica* windbreaks (□——□) and adjacent millet crops (◇– –◇) at (a) the Majjia Valley (DOY 208, 1992) and (b) Sadoré (DOY 214, 1992). Values of $\delta^{18}$O for groundwater (GW) (▲), tree sap (■) and millet sap (◆) are shown for comparison and, inset, the gravimetric moisture content ($\theta_g$) of soil beneath the windbreaks (■——■) and the crop (◆——◆) are shown for each location for reference. Error bars show ±1 s.e.

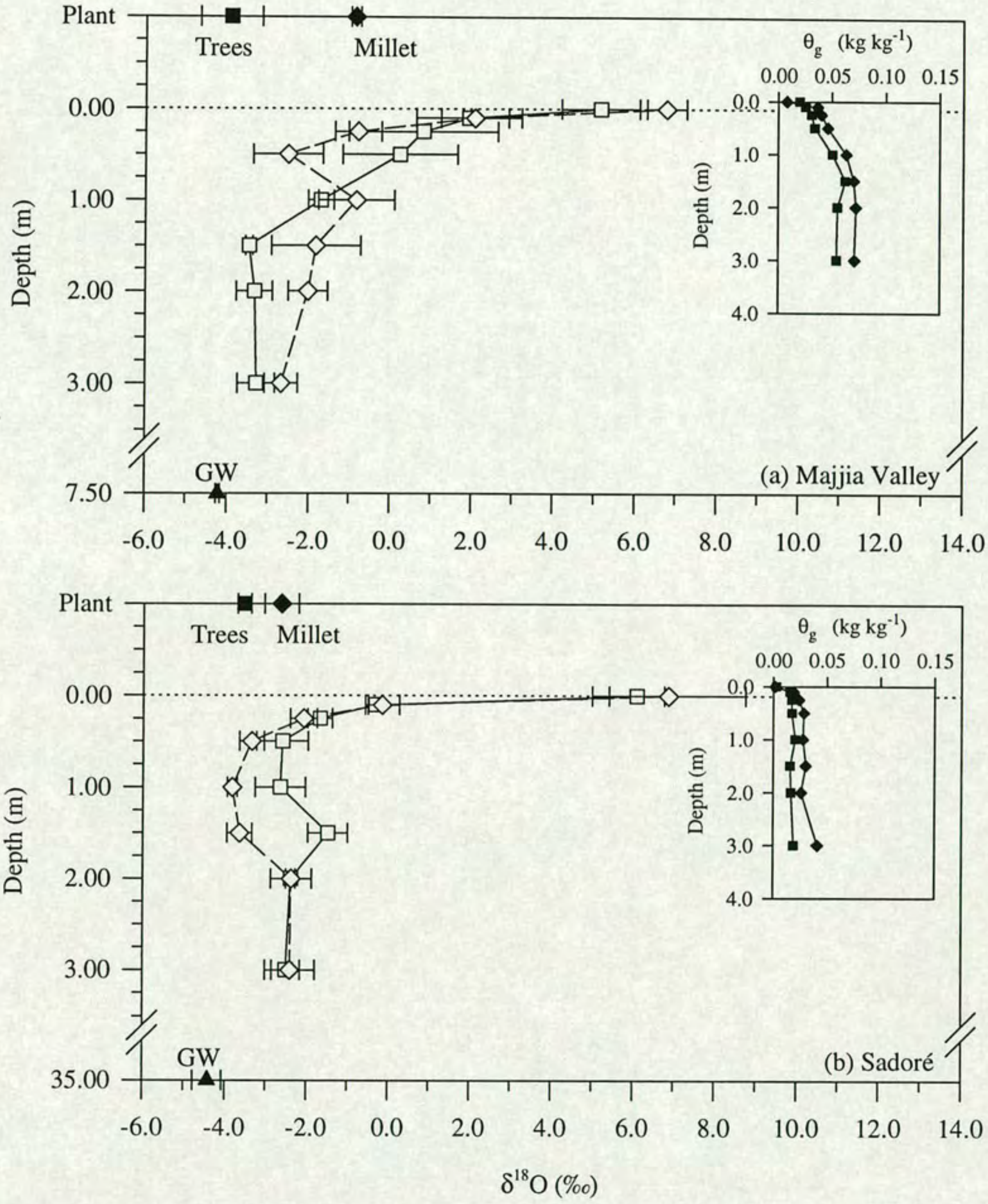


**Figure 3.6:** Profiles of $\delta^{18}O$ values for soil water measured in the late 1993 rainy season beneath *Azadirachta indica* windbreaks (□——□) and adjacent millet crops (◇– –◇) at (a) the Majjia Valley (DOY 266, 1992) and (b) Sadoré (DOY 274, 1992). Values of $\delta^{18}O$ for groundwater (GW) (▲), tree sap (■) and millet sap (◆) are shown for comparison and, inset, the gravimetric moisture content ($\theta_g$) of soil beneath the windbreaks (■——■) and the crop (◆——◆) are shown for each location for reference. Error bars show ±1 s.e.

$$P_s = \left(1 - \frac{|\delta_p - \delta_s|}{|\Delta\delta_l|}\right), \qquad (3.2)$$

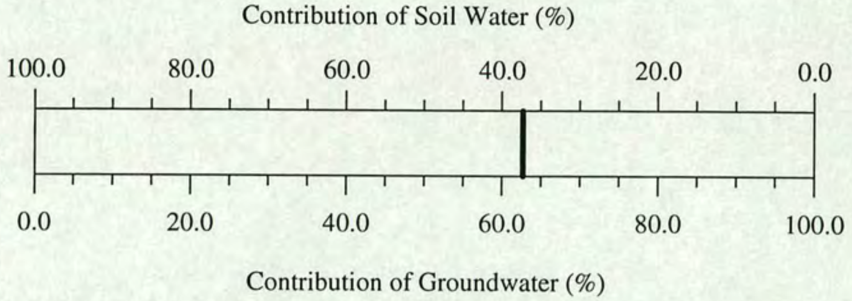
where $\delta_p$ is the isotopic ratio for plant sap expressed using delta notation (Equation 3.1), $\delta_s$ is the δ-value for water from the source in question, and $\Delta\delta_l$ is the difference in δ-values for water from the higher and lower levels of the soil profile. However, values of $P_s$ cannot be determined directly from the data collected at Sadoré and the Majjia Valley in this study because, on any occasion at each location, there are numerous $\delta^{18}O$ values for soil water as a result of the gradients in $\delta^{18}O$ values for water in the soil profile. In order to apply Equation 3.2 to data collected in this study, therefore, it was necessary to estimate mean $\delta^{18}O$ values ($\overline{\delta^{18}O}$) for soil water. This was done by weighting $\delta^{18}O$ values by the quantity of water present in each depth increment of the soil profile using

$$\overline{\delta^{18}O} = \sum_{i=1}^{n} \delta^{18}O_i \left( \frac{\theta_{vi} d_i}{\sum_{i=1}^{n} (\theta_{vi} d_i)} \right), \qquad (3.3)$$

where $\delta^{18}O_i$ is the $\delta^{18}O$ value for the depth increment $i$ out of a total $n$, with volumetric moisture content $\theta_{vi}$ and thickness $d_i$. Use of $\overline{\delta^{18}O}$ values estimated using Equation 3.3 to proportion extraction of soil moisture between two levels in the soil then requires the assumption that the amount of water extracted from any layer within either level of the soil is proportional to the amount of water present in that layer.

Uptake of water by trees was proportioned between groundwater and soil water and uptake of water by millet was proportioned between surface and deeper soil layers using Equation 3.2, with appropriate values for $\delta_s$ and $\Delta\delta_l$ derived using Equation 3.3. An example of the results obtained using this procedure, with values of $\theta_v$ calculated from measured values of $\theta_g$ using a soil bulk density of 1520 kg m$^{-3}$ (Long, 1989), is shown in Fig. 3.7 for the middle of the rainy season, 1993, in the Majjia Valley. The results indicate that the trees were extracting over half their water from groundwater and the millet was extracting most of its water from the top 75 cm of the soil. The proportions determined are not exact, however, because of the assumptions required, and so they should only be regarded as providing support for the conclusions drawn from Fig. 3.5a. This suggests that information drawn from interpretation of the data is as valuable as quantitative assessments

(a) Trees:



(b) Millet:

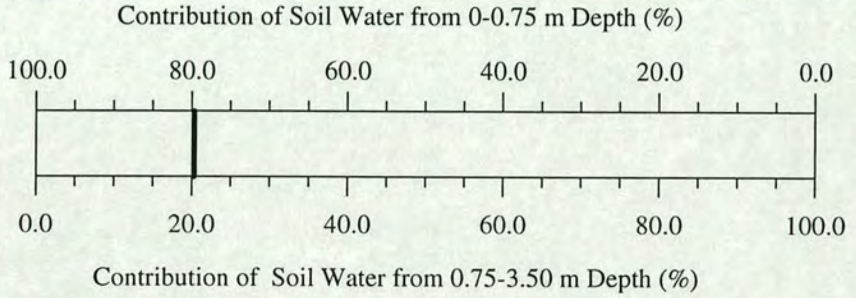


**Figure 3.7:** Nomograms showing the estimated proportions of water taken up from two different sources by (a) the windbreak trees and (b) the millet crop in the Majjia Valley in the middle of the 1993 rainy season (DOY 208, 1993).

of the proportional uptake of water from different sources made using the procedure described here, given the assumptions required.

### 3.4 Conclusions

Proximity of the water table to the surface has important implications for the severity of competition for water between trees and crops when windbreaks are established in semi-arid regions. Results from the Majjia Valley show that where trees have access to groundwater or other deep reserves of soil water, 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 water stress in the crop is unlikely to be aggravated by extraction of water by the trees from the rooting zone of the crop. Where trees do not have access to groundwater, the evidence from Sadoré indicates that the trees fulfil their water requirements from the top 2 to 3 m of the soil throughout the year and that the trees may obtain a portion of the water they require from beneath the crop during dry periods.

Competition for water between windbreak trees and crops is, therefore, only likely to have a large effect on crop productivity at sites where groundwater is not accessible to the trees. When droughts or dry spells occur at these locations, water stress in crop plants growing near the trees is likely to be more severe and occur over longer periods than at sites where trees are able to utilise groundwater. Thus, the availability of groundwater to windbreak trees may explain why millet yields were improved more behind windbreaks in the Majjia Valley (Long, 1989; van den Beldt, 1990) than at Sadoré (Brenner *et al.*, 1993). In the Majjia Valley, the trees are able to use water from at or near the water table when the soil near the surface becomes dry, so that they do not exacerbate water stress in the crop. In contrast, the windbreak trees at Sadoré have to use water from the same layers of the soil as the crop because groundwater is not accessible to roots of the trees and so water use by the trees during dry spells likely causes more severe water stress in adjacent millet. Stomata of millet plants behind windbreaks are, therefore, likely to be closed more often at Sadoré than in the Majjia Valley, so that there is less photosynthesis, less accumulation of dry matter and less improvement in crop yields behind windbreaks at Sadoré. An additional advantage of locations such as the Majjia Valley where groundwater or other deep reserves of soil water are accessible to tree roots is that the productivity of trees at these sites should be higher because they are able to continue growing for a longer period after the rainy season has finished.

This study demonstrated that *A. indica* trees in semi-arid regions can switch from using water near the soil surface to water from deeper sources when the surface becomes dry. No insight was gained, however, into the soil conditions which induce this switch or the duration of the transition. If water potentials in the soil near the surface must fall to low values before the trees begin to use groundwater, then there may be a period while the soil is drying in which competition for water between trees and crops can exacerbate water stress in adjacent crop plants even at sites where trees can use groundwater, although the cumulative effects of such competition over a season should still be less severe at sites where trees are able to utilise groundwater. There is, therefore, a need for research into the sources of water utilised by trees at a location such as the Majjia Valley during consecutive days before and after a rainfall event that breaks a long dry spell. The transition between use of water from the top of the soil profile to use of groundwater could then be followed in the same way as discussed by White *et al.* (1985) for forest trees in North America and, if simultaneous determinations of soil water potentials were made, the water potential of the surface layers of the soil at which the trees begin to use groundwater could be identified. Such research could also identify how quickly roots near the soil surface are reactivated after a period in which the surrounding soil has been extremely dry. It is possible that roots near the surface die or become inactive during long dry spells

(Passioura, 1983, 1988; Nobel and Sanderson, 1984; North and Nobel, 1991), so that uptake of newly fallen rain after a dry spell may be quite slow. There may be differences among tree species in their capacity to efficiently adapt to cycles of wetting and drying by alternating between use of groundwater and water from near the soil surface and such differences could affect the choice of species planted in windbreaks at sites where groundwater is accesible.

Analysis of the sources of water used by trees and crops in agroforestry systems using stable isotope techniques provides a more detailed understanding of the below-ground activity of tree and crop roots than has previously been possible. The data must be interpreted carefully, however, and knowledge of soil moisture profiles is an important aid to drawing useful conclusions, although profiles of soil water potential would be more informative because water potentials are related directly to the availability of water from different soil layers. Large gradients in the isotopic ratios of soil water mean that, at least in semi-arid conditions where soils are very sandy, it is not possible to quantify definitively the proportions of water extracted from different sources by vegetation using simple comparisons of isotopic ratios.

# Chapter 4

# Aerodynamic Conductances of Trees in Windbreaks

## 4.1 Introduction

Fluxes of sensible heat ($H$) from vegetated surfaces can be estimated from measurements of the difference in temperature between the surface of the vegetation and ambient air ($T_s$-$T_a$) using (Monteith, 1981; Monteith and Unsworth, 1990)

$$H = \rho_a c_p (T_s - T_a) g_a \,, \tag{4.1}$$

where $\rho_a$ is the density of dry air, $c_p$ is the specific heat capacity of air at constant pressure and $g_a$ is the bulk aerodynamic conductance for convective heat transfer from the canopy. Derived from Fick's law, $g_a$ represents the integral of eddy diffusivity between the effective source height of heat in the canopy and the height in the constant flux layer above the canopy where $T_a$ is measured (Thom, 1975; Monteith, 1981). For extensive, uniform surfaces where the turbulent boundary layer in the atmosphere above the surface is in equilibrium with the surface and wind speeds increase logarithmically with height, aerodynamic conductances can be calculated from the friction velocity and roughness length associated with the surface (Monteith, 1965; Thom, 1975). Where the turbulent boundary layer above vegetation is not fully adjusted to the surface, however, the wind profile is not logarithmic and cannot be used as a basis for calculating aerodynamic conductances.

Arboreal windbreaks are long, thin lines of trees planted across the prevailing wind direction and so they are not extensive in two dimensions and are taller than surrounding vegetation. Windbreaks thus form an abrupt change in surface roughness with very little horizontal thickness in the direction of the wind and so there is no possibility that the turbulent boundary layer can equilibrate with the canopy of a windbreak. Consequently, aerodynamic conductances for windbreak canopies cannot be determined from theory (Baldocchi *et al.*, 1991), so $H$ cannot be estimated for windbreak canopies using Equation 4.1 unless bulk aerodynamic conductances for heat transfer are measured for trees in the windbreaks.

The bulk aerodynamic conductance for whole trees can be measured directly. If a tree is wetted until the crown is saturated, the aerodynamic conductance for the tree crown can be calculated from the rate at which the water evaporates from the tree, provided that the difference in vapour pressure between the surface of the tree and ambient air is known. Teklehaimanot and Jarvis (1991) employed this principle to measure aerodynamic conductances for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) trees in a Scottish agroforestry trial, measuring rates of evaporation after wetting by recording the rate of change in the mass of excised trees suspended from a tripod. A drawback of their "hanging-tree" technique is that it requires destruction of the trees studied and so it is not possible to make measurements on a more than a very few trees where removal of trees will alter the environment of a site.

An alternative approach is to measure or estimate conductances for heat transfer across the boundary layers of individual leaves inside the crown of a tree and extrapolate these to the whole crown by treating boundary layer conductances for individual leaves as conductances in parallel. Boundary layer conductances for leaves can be estimated from equations developed by engineers for calculating coefficients for heat transfer from metal plates and other objects (Kreith, 1973; Schuepp, 1993) or from an empirical equation for boundary layer conductances of mutually sheltered leaves in tree crowns that Landsberg and Powell (1973) developed from measurements in a wind tunnel on an artificial tree with blotting paper leaves. Leaf boundary layer conductances can be measured by solving the energy budget of individual leaves (Pearman *et al.*, 1972) or by measuring the difference in temperature between a pair of real leaves, one of which is coated with petroleum jelly to prevent transpiration (Thorpe and Butler, 1977), but these methods require some estimate of net radiation fluxes to individual leaves.

Measurements of leaf boundary layer conductances may also be made on models of leaves. The simplest such method involves measuring the rate of water loss from saturated leaf models constructed from blotting paper (Grace and Wilson, 1976; Jones, 1992), but heat transfer methods require construction of models from metal that can be heated electrically. Such models can be heated above ambient temperature in an environment where net radiation is zero and boundary layer conductances calculated from the rate at which the model cools (Pearman *et al.*, 1972; Grace *et al.*, 1980; Jones, 1992) or from the input of electrical power to the model at a known difference in temperature between the model and ambient air (Dixon and Grace, 1983; Chen *et al.*, 1988). Pairs of leaf replicas, one heated and one unheated, can be used to measure boundary layer conductances where net radiation flux to the models is not zero (Pearman *et al.*, 1972) and the method has been improved sufficiently in recent years to allow measurements to be made in the field (Leuning, 1989; Leuning and Foster, 1990; Brenner, 1991; Brenner and Jarvis, 1995). Of all these methods, only the latter is suitable for use inside tree crowns in the field because it is easily automated (Brenner, 1991) and does not require net radiation to be nil or measurements of wind speeds or net radiation near leaves.

Aerodynamic conductances for trees in windbreaks at a site in the Sahel were required for estimation of values of $H$ for trees in windbreaks on the basis of Equation 4.1. The hanging-tree method could not be used for all of the trees studied because removal of each of these trees from the windbreaks was not possible. Measurements of aerodynamic conductances for whole trees in windbreaks were consequently made using both the hanging-tree method and by scaling up leaf boundary layer conductances measured using heated leaf-replica pairs to whole tree crowns. Values measured using each method were compared in order to test whether they are equivalent and whether bulk aerodynamic conductances for whole trees can be derived from measurements of boundary layer conductances for individual leaves inside the tree crown.

## 4.2 Theory

### **4.2.1** *Heat transfer theory*

Boundary layer conductances for objects of a variety of shapes can be calculated using standard equations derived from heat transfer theory for use in engineering studies (Kreith, 1973; Monteith and Unsworth, 1990). From theory, the conductance for heat transfer by forced convection through the boundary layer over one side of a smooth, flat plate ($g_b'$) is given by (Kreith, 1973; Schuepp, 1993)

$$g_b' = \frac{\kappa \mathrm{Nu}}{d} \tag{4.2a}$$

where $\kappa$ is the thermal diffusivity of air, $d$ is the characteristic dimension of the plate and Nu is a dimensionless coefficient known as the Nusselt number. The value of Nu is given by (Kreith, 1973; Schuepp, 1993)

$$\mathrm{Nu} = 0.664\,\mathrm{Pr}^{0.33}\,\mathrm{Re}^{0.5} \tag{4.2b}$$

for boundary layers in which the flow of air is laminar and by

$$\mathrm{Nu} = 0.036\,\mathrm{Pr}^{0.33}\,\mathrm{Re}^{0.8} \tag{4.2c}$$

for boundary layers in which flow is turbulent, where Pr is the Prandtl number and Re is the Reynolds number. Pr is the ratio $\upsilon/\kappa$, where $\upsilon$ is the kinematic viscosity of air, and $\mathrm{Re}=(ud/\upsilon)$, where $u$ is free stream wind speed. Thus, theoretically, conductances for heat transfer through boundary layers are expected to be proportional to $u^{0.5}$ when laminar and to $u^{0.8}$ when turbulent. Values of $g_b'$ can be calculated for an irregularly shaped leaf on the basis of this theory by estimating *d* as the mean length of the leaf in the direction of the airstream (Grace, 1983; Monteith and Unsworth, 1990).

**4.2.2** *Heated leaf-replica pairs*

Boundary layer conductances ($g_b$) for convective heat transfer from leaves can be measured using pairs of identical leaf replicas, one heated electrically and one unheated. Provided that the emissivity of the replicas is low, energy absorbed by them is very largely dissipated by convection, so that, as described by Leuning (1989), convective heat loss can be calculated for the heated replica from

$$R_{nH} + P_i = \rho_a c_p (T_{sH} - T_a) g_b \tag{4.3a}$$

and, for the unheated replica, from

$$R_{nU} = \rho_a c_p (T_{sU} - T_a) g_b , \tag{4.3b}$$

where $R_{nH}$ and $R_{nU}$ are the net radiation absorbed by the heated and unheated replicas, respectively, $P_i$ is the electrical power supplied to the heated replica per unit projected area of the replica, $T_{sH}$ and $T_{sU}$ are the surface temperatures of the heated and unheated replicas, respectively, and $T_a$ is the ambient air temperature. If the two replicas are similarly exposed to radiation, it can be assumed that $R_{nH}$=$R_{nU}$, so that on subtracting Equation 4.3b from Equation 4.3a, $g_b$ can be calculated from

$$g_b = \frac{P_i}{\rho_a c_p (T_{sH} - T_{sU})} \tag{4.4}$$

using measured values of $P_i$ and ($T_{sH}$-$T_{sU}$). Corrections for increased long-wave emittance from the heated replica should be applied using Stefan's law (although for the models used in this study, this correction was minor, being only ≈5 % of measured boundary layer conductances at wind speeds of 0 m $s^{-1}$ and <2 % at moderate wind speeds). Values of $g_b$ determined in this way are conductances for transfer from both sides of a leaf expressed per unit of projected leaf area, whereas values of $g_b'$ calculated using Equation 4.2a are conductances for one surface of the leaf only. Thus $g_b$ is equivalent to $2g_b'$ for symmetrical leaves.

### **4.2.3** *The "hanging-tree" method*

As described by Teklehaimanot and Jarvis (1991), in order to estimate bulk aerodynamic conductances for tree crowns using the hanging-tree technique, a tree is cut and suspended from a load cell attached to a tripod for support. The tree is sprayed with water until the storage capacity of the crown is reached and, beginning at the point in time when drainage from the tree ceases, the rate of change in the mass of the tree is recorded while the surface temperature of the canopy remains approximately equal to the wet bulb temperature. Thus the evaporation rate ($E_{\mathrm{ht}}$) from the saturated tree crown is measured directly. $E_{\mathrm{ht}}$ is used to calculate the aerodynamic conductance for water vapour transfer ($g_{\mathrm{aV}}$) from the tree using (Teklehaimanot and Jarvis, 1991)

$$g_{\mathrm{aV}} = \frac{\gamma\lambda}{\rho_{\mathrm{a}} c_p} \frac{E_{\mathrm{ht}}}{(e^*(T_{\mathrm{s}}) - e_{\mathrm{a}})} \tag{4.5}$$

where $\gamma$ is the psychrometric constant, $\lambda$ is the latent heat of vaporisation, $e^*(T_{\mathrm{s}})$ is the saturation vapour pressure at surface temperature, and $e_{\mathrm{a}}$ is the vapour pressure at reference height. The similarity hypothesis states that the eddy diffusivities of heat and vapour, and therefore their aerodynamic conductances, are equal when air is fully turbulent because transfer then depends on the eddy structure of the air flow rather than properties of the entities undergoing transfer (Monteith, 1965; Thom, 1975; Monteith, 1981). Values of $g_{\mathrm{aV}}$ can, consequently, be converted to aerodynamic conductances for heat transfer ($g_{\mathrm{aH}}$) from the tree using

$$g_{\mathrm{aH}} = g_{\mathrm{aV}} \tag{4.6}$$

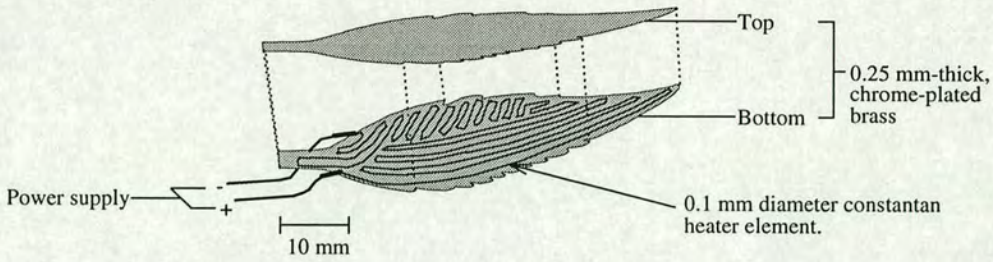
on the assumption that the locations of the effective sources of heat and vapour within the crown are the same. The bulk aerodynamic conductance for the tree crown can then be denoted simply as $g_{\mathrm{a}}$.

## 4.3 Materials and methods

### **4.3.1** *Site description*

The field experiments undertaken for this study were carried out at the research farm of the ICRISAT Sahelian Centre at Sadoré (13°14'N, 2°16'E), about 45 km south of Niamey, the capital of Niger. All measurements were made on *Azadirachta indica* A. Juss. trees growing in windbreaks formed by a double row of alternately planted trees, with 1.5 m between rows and 3 m between trees in the same row. Windbreaks at the site ran north-south and were 50 m long with 30 m of cropland between parallel windbreaks. They

(a) Split-view:



(b) View from below:

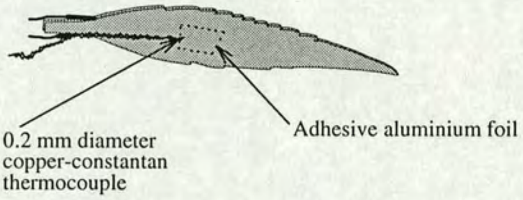


**Figure 4.1:** (a) Construction of a heated replica of an *Azadirachta indica* leaflet and (b) the underside of the replica showing the position of the copper-constantan thermocouple junction.

were managed as hedge windbreaks and so were pruned back to 2 m from a height of 4 to 5 m at the end of every dry season.

### **4.3.2** *Leaf replica construction*

*A. indica* has large, compound leaves and so replicas of leaflets were used in this study, the size and shape of which were copied from the outline of a typical *A. indica* leaflet traced at the site. The replicas were 61 mm and 24 mm at their longest and widest points, respectively, and as illustrated in Fig. 4.1, they were constructed by sandwiching a heater element, made from 39 cm of 0.1 mm-diameter constantan wire with a resistance of 19.5 Ω, between two pieces of chrome-plated, 0.25 mm-thick brass sheeting. The heater elements were insulated from the brass using double-sided cellotape, which, with five drops of epoxy adhesive, also served to bond together the two sides of each replica. A single thermocouple junction, made from 0.2 mm diameter teflon-coated copper-constantan wire (TC Ltd., Uxbridge, UK.), was attached to the lower sides of each replica using adhesive aluminium foil, with the thermocouple junctions attached to each pair of replicas connected by a common constantan wire, so that ($T_{sH}$-$T_{sU}$) could be measured directly.

### **4.3.3** *Wind tunnel tests*

One pair of heated replicas of *A. indica* leaflets was tested in the wind tunnel at the Institute of Ecology and Resource Management at the University of Edinburgh. Details of the design and construction of the wind tunnel are given by Dixon (1982). Values of $g_b$ were determined in initially laminar flow at wind speeds ranging from 0 to approximately 10 m $s^{-1}$, as measured by the Pitot tube in the wind tunnel, with the replicas at inclination angles (relative to horizontal) of 0, 20, 40, 60 and 80°. Two sets of measurements were made, one with the wind parallel to the long axes of the replicas and one with the wind parallel to the short axes. A portable power supply maintained the voltage across the heated replica at close to 1.12 V, from which $P_i$ was calculated, and a data logger (21X, Campbell Scientific Ltd., Shepshed, UK.) recorded ($T_{sH}$-$T_{sU}$) every 5 s and calculated averages at 1 min intervals. Measurements were made for a minimum of 2 min after ($T_{sH}$-$T_{sU}$) had equilibrated at each wind speed.

### **4.3.4** *Deployment of leaf replicas in the field*

When deployed in the field, nine pairs of replicas were mounted in the crown of a tree in a windbreak, with three replica pairs in each of three horizontal layers of the canopy (Fig. 4.2a). Each pair of replicas was mounted on a plastic arm attached to a small, brass universal joint (Fig. 4.3) that was fixed to a branch in the canopy using plastic cable ties. The universal joints allowed each pair of replicas to be fixed at a similar inclination angle to the surrounding leaves at each position in the canopy.

The nine pairs of replicas were connected in series in two circuits, with one replica from each pair connected to each circuit (Fig. 4.2b). Relay switches alternated the supply of power between the two circuits and turned the power on and off in a cycle lasting 60 min. Power was initially supplied to one of the circuits for 15 min, so that one replica in each pair was heated, before power to the replicas was switched off and neither replica heated for 15 min. Power was then supplied to the second circuit for 15 min, so that the second replica in each pair was heated, before power was again switched off for the final 15 min of the cycle. This ensured that $g_b$ was measured with each replica in a pair heated alternately, thus eliminating errors resulting from bias, and also provided periods when neither replica in each pair was heated, so that offset values of ($T_{sH}$-$T_{sU}$) resulting from differential shading of the replicas could be measured. Opening of the relay switches was controlled by a 21X data logger using a circuit described by Brenner (1991).

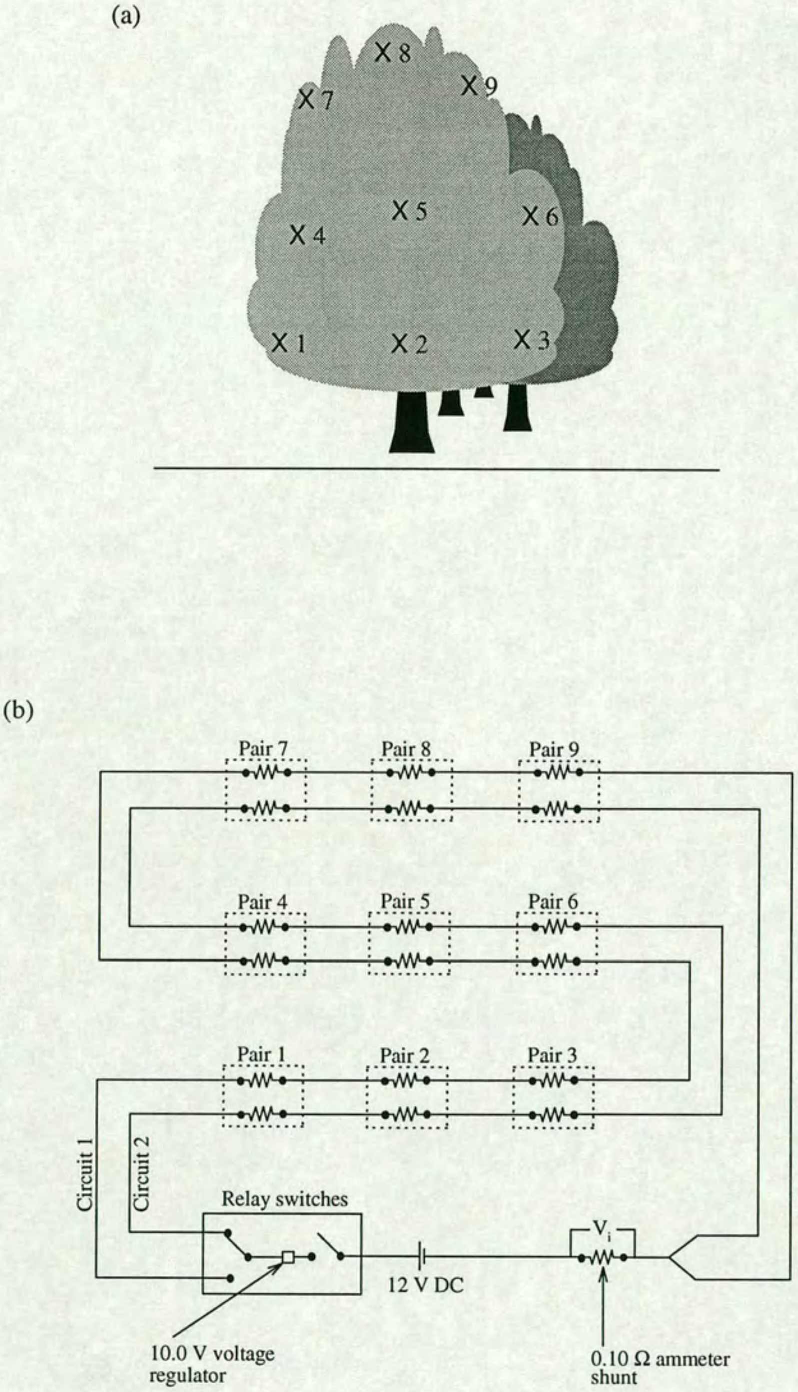


**Figure 4.2:** (a) Cross-sectional view through a double-row windbreak showing the approximate positions (X) of the three heated leaf-replica pairs mounted in each of three layers of the crown of a tree in the windbreak in order to measure leaf boundary layer conductances; and (b) the electrical circuit used to power the nine heated leaf replicas when mounted in the tree.

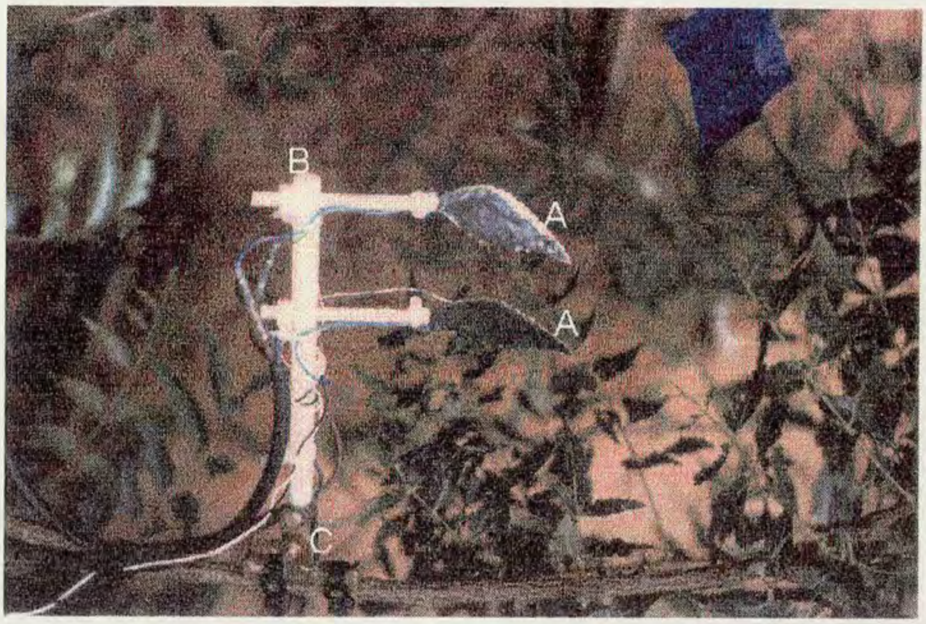


**Figure 4.3:** A pair of replicas of *Azadirachta indica* leaflets (A) used to measure leaf boundary layer conductances. The replicas were mounted on a plastic arm (B) attached to a brass universal joint (C) that was fixed to a branch within the crown of a tree using plastic cable ties. The universal joint allowed the replicas to be oriented at any desired angle.

**Figure 4.4:** An *Azadirachta indica* tree (C) in a windbreak at Sadoré suspended from a load cell hanging from the apex of a tripod constructed from steel pipe (A). Nozzles (B) mounted on the legs of the tripod were used to spray water onto the tree and reference meteorological data were measured with a psychrometer, anemometer and wind vane mounted adjacent to the windbreak (not shown).

Power to heat the replicas was supplied by a 12 V battery, with the voltage across the entire circuit ($V_i$) maintained at 10.0 V using a voltage regulator. Current ($I_i$) through the replicas was determined from the voltage across a 0.10 Ω ammeter shunt in the circuit and $P_i$ calculated from

$$P_i = \frac{V_i I_i}{9 A_r} \tag{4.7}$$

where $A_r$ is the projected area of each replica, 8.4 cm$^2$ for the replicas of *A. indica* leaflets used here, and the factor 9 in the denominator accounts for the nine replica pairs in the circuit.

### **4.3.5** *Collection of data from leaf replicas*

Measurements of $g_b$ were made on four trees over four periods, first on Tree O92 between DOY 277 and 293, 1992, and then, during 1993, on Tree A93 from DOY 114 to 126, on Tree J93 for the period DOY 193 to 203 and on Tree S93 between DOY 260 and 271. During each period, ($T_{sH}$-$T_{sU}$) for each of the nine replica pairs and $I_i$ were recorded every 30 s and averaged every 10 min using a 21X data logger and a multiplexer (AM32, Campbell Scientific Ltd., Shepshed, UK.). Data were not recorded in the initial 5 min of either heating or cooling in order to allow the temperatures of the replicas to reach steady-state. Wind speeds measured using a cup anemometer (A100R, Vector Instruments Ltd., Rhyl, UK.) mounted adjacent to the western side of the windbreak at a height of 4 m above the ground were also logged.

At the end of each period of measurement, the projected crown area ($A_c$) of each tree was estimated from measurements of the radius of the perimeter of the tree crown, as described in Chapter 2. The leaves of each tree were then harvested in layers which divided the tree crown evenly into three and projected leaf area for each layer ($A_{lj}$) estimated as the product of the total dry mass and specific leaf area of leaves in each layer. Specific leaf areas were calculated as the ratio of projected leaf areas, measured using a leaf area meter (Li-3100, Li-Cor Inc., Lincoln NE, USA.), and dry mass of a subsample of leaves harvested from each layer. Total leaf area ($A_t$) was then found by summing $A_{lj}$ for all layers of the crown.

### **4.3.6** *Extrapolation of* $g_b$

Values of $g_b$ were determined using Equation 4.4 for each 10 min time-step in which replicas were heated. Prior to calculation of $g_b$, however, data were screened and eliminated on the basis of four criteria. Firstly, data were not used if measured during periods of rainfall or soon afterwards, Secondly, if ($T_{sH}$-$T_{sU}$) was ≤0.5 °C, the precision of $g_b$ values became very low and so these values were eliminated from the analysis. Third, if the difference between the offset temperature measured before and after heating was >1.0 °C, data were not used because this indicates that differential radiation loads on the replicas in a pair changed substantially during the measurement period. Finally, data were not used if mean wind speed during the measurement period was ≤0.30 m s$^{-1}$, as this was the stall speed of the anemometer.

The summed leaf boundary layer conductances for each tree ($g_{bt}$) were calculated by integrating measured values of $g_b$ over the total leaf area of each tree crown on the assumption that boundary layer conductances for all individual leaves in a tree crown are conductances in parallel. Thus $g_{bt}$ is given by

$$g_{\mathrm{bt}} = \sum_{j=1}^{3} (\overline{g_{\mathrm{b}j}} A_{\mathrm{l}j}), \tag{4.8}$$

where $\overline{g_{bj}}$ is the mean value of $g_b$ measured in each layer of the tree crown.

### **4.3.7** *Use of the hanging-tree method on trees in windbreaks*

The hanging-tree method was used to measure $g_a$ values for two *A. indica* trees growing in the hedge windbreaks at the ICRISAT Sahelian Centre. The first, Tree HT1, was cut from the eastern face of a windbreak on DOY 284, 1993 and the second, Tree HT2, from the western face on DOY 287, 1993. Before cutting each tree, branches of neighbouring trees likely to encroach on the hanging tree and branches of the hanging tree likely to touch the legs of the tripod were pruned back. The tripod was made from three 6 m lengths of 5 cm o.d. steel pipe joined at the apex using a specially fabricated set of clamps. The tree was attached to a 250 kg-capacity load cell (RS Components Ltd., Corby, UK.) suspended from the tripod using nylon rope before it was cut near the soil surface and sprayed with water from three nozzles mounted on the legs of the tripod and a fourth, hand-held nozzle (Fig. 4.4). The water was transported to the field site in a 210 dm$^3$ plastic barrel and pumped to the nozzles using a submersible pump powered by a portable generator. When the tree was thoroughly soaked, spraying was stopped and excess water allowed to run off. The time at which dripping from the cut trunk ceased was noted or a bucket was tied on to the bottom of the trunk after water stopped running off the trunk in a continuous stream. The tree was then allowed to dry while its mass was logged every 10 s on a 21X data logger.

The data logger also recorded wind speed, wind direction, air temperature and air vapour pressure deficit, measured at a height of 4 m at the western face of the windbreak using a cup anemometer (A100R, Vector Instruments Ltd., Rhyl, UK.), a wind vane (W200, Vector Instruments, Rhyl, UK.) and an aspirated psychrometer (Allen *et al.*, 1994). The temperature of the surface of the crown was measured using thermocouple junctions, made from 0.2 mm diameter copper-constantan wire, connected in parallel and attached to the lower surfaces of five leaves in each of three layers of the crown with porous surgical tape. Reference junctions of the thermocouples were located at the dry bulb of the psychrometer and so mean leaf-air temperature difference for each layer was measured directly.

Leaf-air temperature differences for each layer of the tree crown were weighted by the leaf area in each layer in order to calculate the average surface temperature of the crown. Values of $g_a$ were then determined from Equations 4.5 and 4.6 using data averaged over periods of 120 s between the point at which run off from the tree was negligible and the point at which the surface temperature of the canopy began to diverge from the wet bulb temperature. The experiment was repeated eight times on each tree before the projected area of the tree crown ($A_c$) and the total leaf area of each tree ($A_t$) were determined using the same methods used for the leaf-replica experiments.

### **4.3.8** *Data analysis*

Values of $g_{bt}$ and $g_a$ were plotted against wind speed and equations were fitted to the data by non-linear regression using SPSS statistical software.

## 4.4 Results and discussion

### **4.4.1** *Wind tunnel tests*

Values of $g_b$ for horizontal replicas of *A. indica* leaflets measured in the wind tunnel increased with $u$ and were higher when the short axes of the replicas were aligned parallel to the airstream, as shown in Fig. 4.5, confirming expectations from Equations 4.2a, 4.2b and 4.2c. Also plotted in Fig. 4.5 are lines showing $2g_b'$ for laminar boundary layers of horizontal replicas calculated on the basis of heat transfer theory for smooth, flat plates under conditions of forced convection (Equations 4.2a and 4.2b), assuming that the contribution of free convection to transfer was negligible. Measured values of $g_b$ exceeded these theoretical values at all values of $u>0$, particularly at high wind speeds (Fig. 4.5). Such enhancements to values of $g_b$ measured using leaf models have been observed by many others (see Schuepp, 1993) and most likely resulted from instabilities in the boundary layers of the replicas caused by their irregular shape and serrated edges, in addition to transfer by free convection at low $u$ that is not accounted for by Equations 4.2a and 4.2b and increasing turbulence in the boundary layers at high $u$ (Monteith and Unsworth, 1990; Schuepp, 1993).

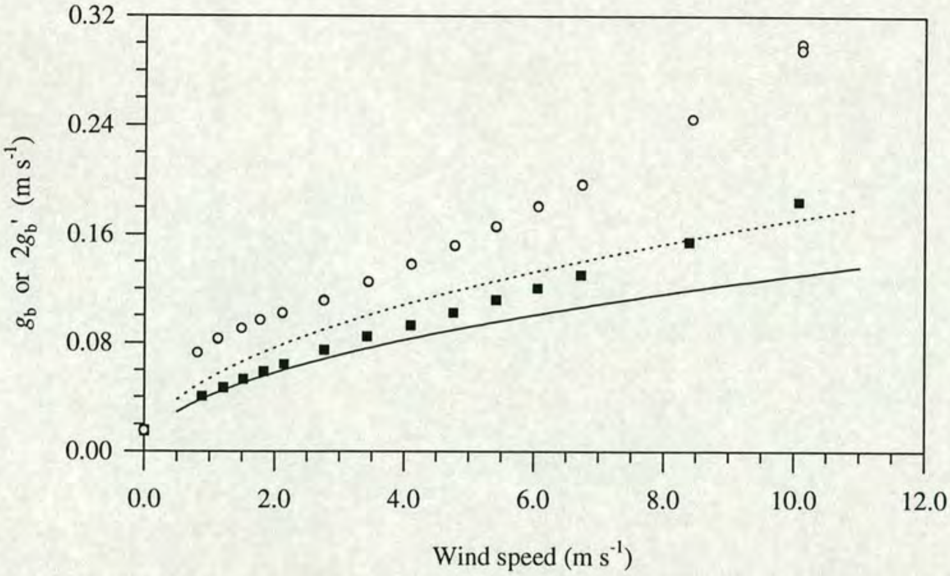


**Figure 4.5:** Values of boundary layer conductance ($g_b$) for horizontal replicas of *Azadirachta indica* leaflets at various wind speeds in initially laminar flow in a wind tunnel with the airstream parallel to the long (■) and short (○) axes of the replicas. Also shown are conductances for laminar boundary layers ($2g_b'$) of horizontal replicas calculated on the basis of heat transfer theory for smooth, flat plates under conditions of forced convection (Equations 4.2a and 4.2b) with flow along the long (———) and short (·········) axes of the replicas.

The transition from laminar to turbulent flow in the boundary layers of the replicas should be marked, according to Equations 4.2b and 4.2c, by a shift from $g_b \propto u^{0.5}$ to $g_b \propto u^{0.8}$. Changes in the exponent of $u$ in the relationship between $g_b$ and $u$ can be seen as changes in slope when $\ln(g_b)$ is plotted against $\ln(u)$. Thus, the slopes of the linear regression lines in Fig. 4.6 show that, for flow parallel to the long axes of the replicas, $g_b$ was proportional to $u^{0.55}$ at low $u$ and to $u^{0.80}$ at high $u$, with the transition from laminar to turbulent boundary layers at $u \approx 5.1$ m s$^{-1}$. For flow along the short axes of the replicas, the transition occurred at $u \approx 3.9$ m s$^{-1}$, with $g_b$ proportional to $u^{0.36}$ at lower $u$ and to $u^{0.86}$ at higher $u$ (Fig. 4.6). The value of the Reynolds number at the onset of turbulence in the boundary layers of the replicas was Re≈8600 for flow along the long axes of the replicas and Re≈3800 for flow along the short axes. These values are much lower than the critical value of Re≈$2 \times 10^4$ expected for transition to turbulence over smooth, flat plates (Monteith, 1965; Schuepp, 1993), probably because of the shape and serrations present on the replicas (Grace, 1983; Schuepp, 1993), but they are closer to the value of Re≈8800 reported by Grace and Wilson (1976) for models of *Populus* leaves in the same wind tunnel.

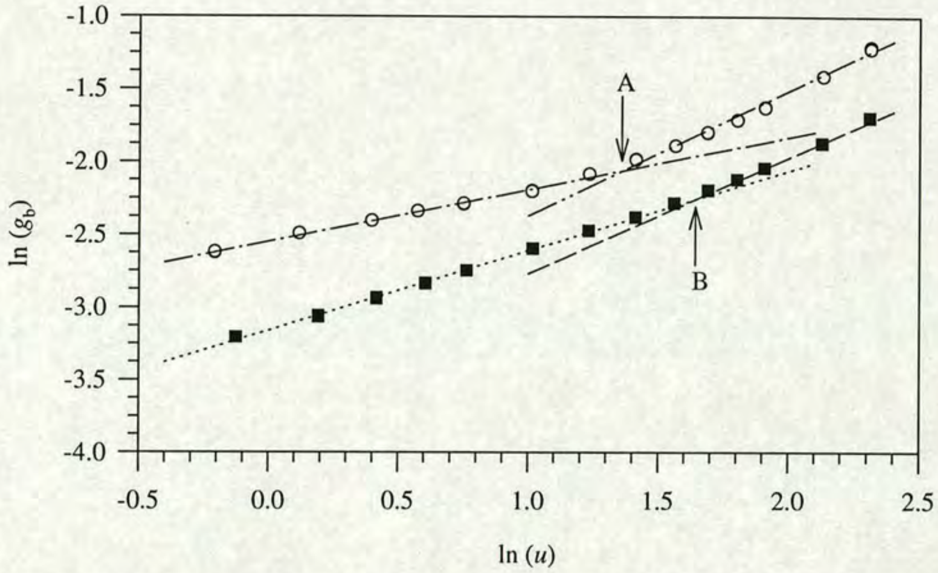


**Figure 4.6:** Logarithmic values of boundary layer conductances ($g_b$) for horizontal replicas of *Azadirachta indica* leaflets plotted against the logarithm of wind speed ($u$). Measurements were made in the wind tunnel in initially laminar flow with the long (■) and short (○) axes of the replicas parallel to the airstream. A and B indicate changes in the slopes of lines fitted to the data by linear regression which approximately mark the transition from laminar to turbulent flow in the boundary layers of the replicas.

Enhancement of $g_b$ for leaf models above $2g_b'$ is often expressed as a constant multiplier, $\beta$, applied to Equations 4.2b and 4.2c (Monteith and Unsworth, 1990; Schuepp, 1993). $\beta$ was evaluated for the data in Fig. 4.5 and was found to be 1.08 and 1.39 for laminar and turbulent boundary layers, respectively, in flow parallel to the long axes of the replicas. For flow along the short axes of the replicas, $\beta$ was 1.31 for laminar boundary layers and 1.92 for turbulent boundary layers. These values lie within the range of values observed by others ($1.0 \leq \beta \leq 2.5$) and are reasonably close to the average expected value of $\beta \approx 1.5$ (Schuepp, 1993). In general, therefore, the results of the tests undertaken in the wind tunnel demonstrated that values of $g_b$ measured using the heated leaf-replica pairs constructed for use in this study showed responses to $u$ that deviated from heat transfer theory for flat plates in a manner consistent with deviations from theory caused by the aerodynamic properties of leaves that have been observed by others in experiments with leaf replicas.

The effect of the angle of inclination ($\Theta$) on boundary layer conductances is usually expressed using the ratio $\alpha$, where $\alpha = g_b(\Theta)/g_b(\Theta=0)$ (Schuepp, 1993). Values of $\alpha$ determined for models of *A. indica* leaflets at several $\Theta$ are plotted in Fig. 4.7 and, as shown, the orientation of the long and short axes of the replicas relative to the airstream

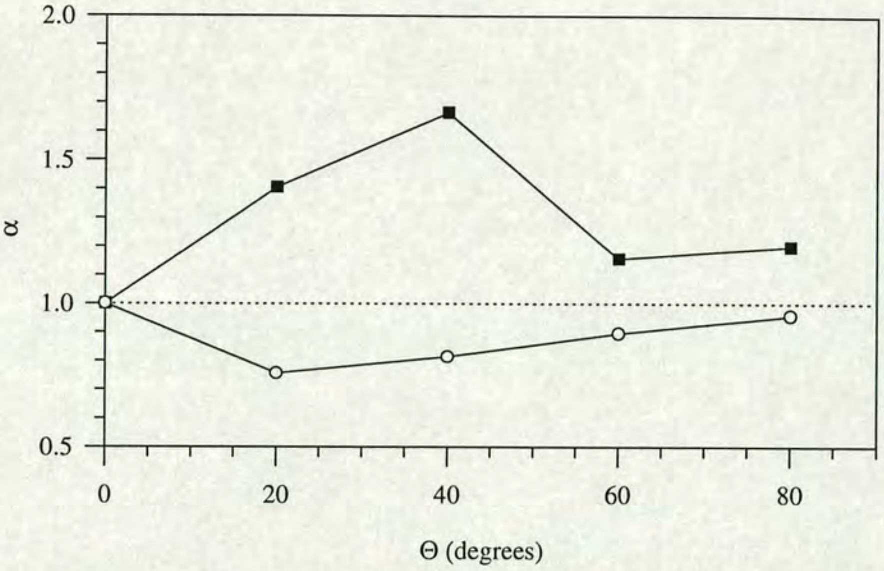


**Figure 4.7:** The effect of the angle of inclination (Θ) relative to horizontal of replicas of *Azadirachta indica* leaflets on the ratio α for flow along the long (■) and short (○) axes of the replicas, where $\alpha=g_b(\Theta)/g_b(\Theta=0)$ and $g_b$ is the boundary layer conductance of the replicas measured in the wind tunnel in initially laminar flow at a wind speed of 2.75 m $s^{-1}$.

caused marked differences in α. The same phenomenon was observed Parkhurst *et al.* (1968) and Schuepp (1993), who concluded from electrochemical visualisations of transfer that it occurs because the wake on the leeward side of plates or leaf replicas makes contact with the surface only when the streamwise length of the replica is large relative to the width. Transfer of heat at $\Theta>0$ is thus enhanced relative to transfer from horizontal surfaces when the long axes of replicas are parallel to flow but depressed when air flows parallel to the short axes. The data in Fig. 4.7 stress, consequently, the importance of orienting leaf replicas at the same angle of inclination as surrounding leaves when they are deployed in the field to measure $g_b$.

### **4.4.2** *Leaf boundary layer conductances in the field*

Mean values of $g_b$ for model leaflets of *A. indica* in each of the three horizontal layers of the crown of Tree O92 are plotted over the course of DOY 288, 1992 in Fig. 4.8 together with concurrent measurements of $u$ at the top of the windbreak. The data shown are typical of other days and other trees on which measurements were made with heated leaf-replica pairs. Values of $g_b$ varied with $u$, as expected, and tended to be higher in the top layer of the crown of each tree than at lower levels because $u$ tends to increase with height and because upper layers of the trees were less densely foliated than lower layers, so that there was probably less mutual sheltering of leaves (Landsberg and Powell, 1973;

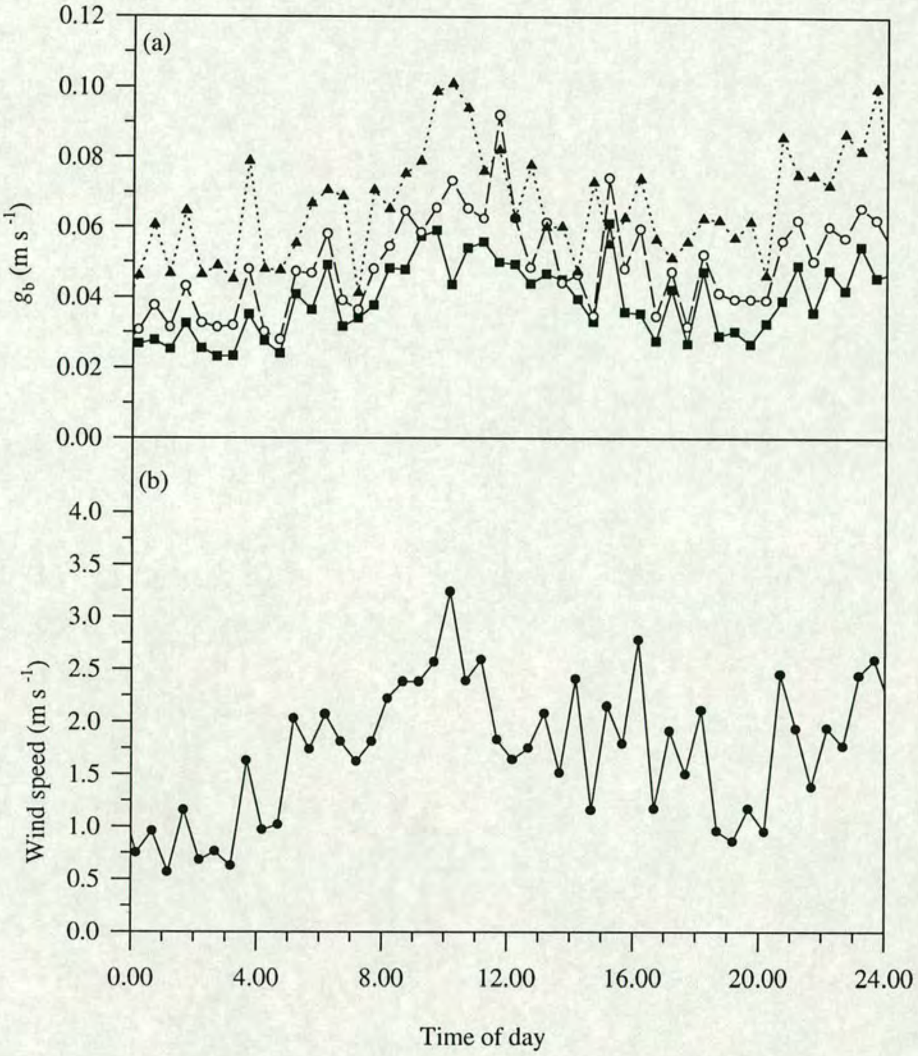


**Figure 4.8:** (a) Mean boundary layer conductances ($g_b$) (n=3) for model leaflets of *Azadirachta indica* in the top (▲·······▲), middle (○— —○) and bottom (■——■) thirds of the crown of an *A. indica* tree in a windbreak at Sadoré on DOY 288, 1992; and (b) concurrent wind speed at the top of the windbreak.

Schuepp, 1993) and, therefore, higher boundary layer conductances near the tops of the trees.

### **4.4.3** *Summed leaf boundary layer conductances for whole trees*

Figure 4.9 shows values of $g_{bt}$ calculated from values of $g_b$ using Equation 4.8 for each of the trees in which leaf replicas were deployed. Note that the units of conductance for $g_{bt}$ are m$^3$ s$^{-1}$ because conductances per unit leaf area have been integrated over the total leaf area of each tree, so that $g_{bt}$ is a conductance per tree rather than per m$^2$.

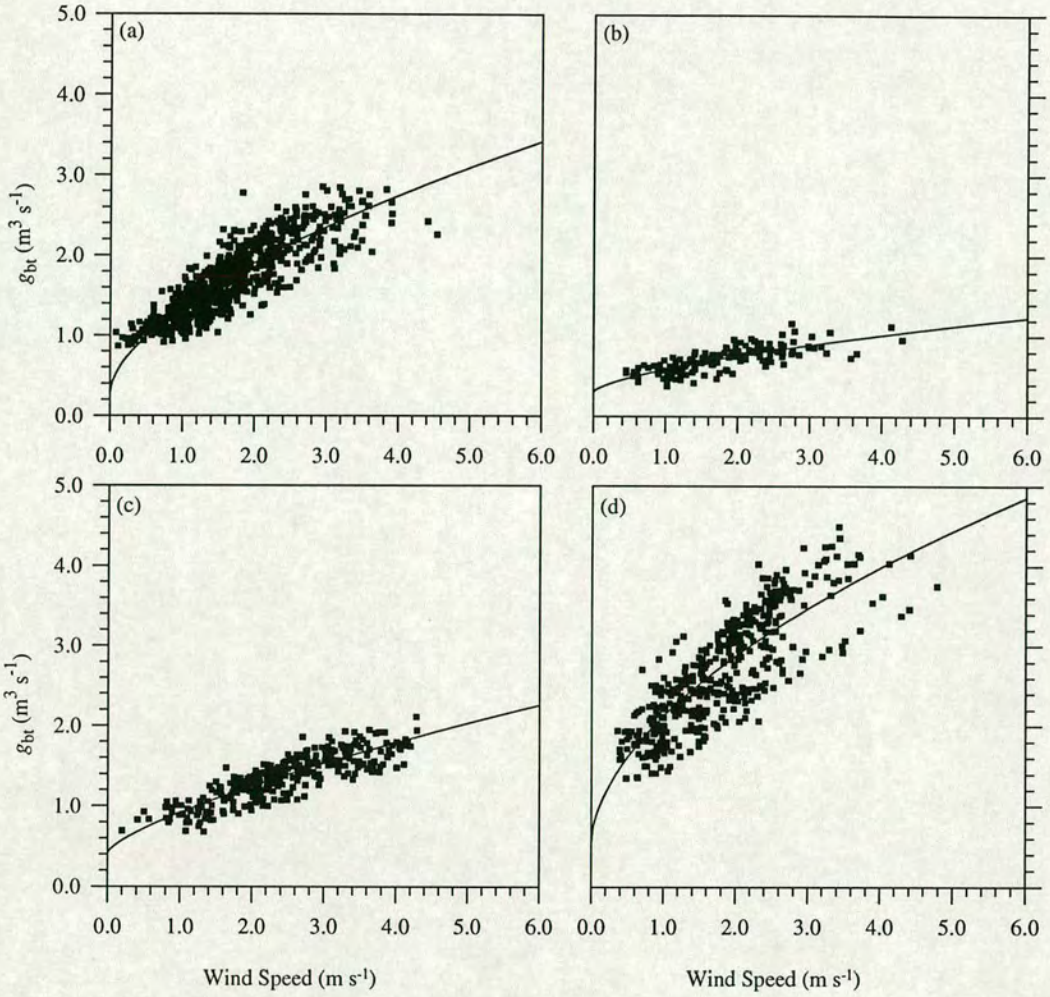


**Figure 4.9:** Dependence of the summed leaf boundary layer conductance for tree crowns ($g_{bt}$) on wind speed for canopies of *Azadirachta indica* trees in windbreaks. Values were determined using heated leaf-replica pairs in (a) Tree O92, (b) Tree A93, (c) Tree J93 and (d) Tree S93. Equations for the fitted lines are given in Table 4.2.

**Table 4.1:** Tree height, leaf area ($A_t$) and projected crown area ($A_c$) for the *Azadirachta indica* trees in windbreaks at Sadoré for which aerodynamic conductances were measured.

| Tree Label | Tree height (m) | $A_t$ (m$^2$) | $A_c$ (m$^2$) |
|---|---|---|---|
| O92 | 4.2 | 35.7 | 5.7 |
| A93 | 4.2 | 12.3 | 6.6 |
| J93 | 2.9 | 26.0 | 5.1 |
| S93 | 4.2 | 55.8 | 6.4 |
| HT1 | 4.3 | 42.1 | 6.2 |
| HT2 | 3.9 | 21.9 | 4.7 |

Figure 4.9 shows that there were substantial differences among trees in the magnitude of $g_{bt}$ at any particular $u$. These differences resulted primarily from differences among trees in leaf areas ($A_t$) (Table 4.1) because there was little variation among trees in values of $g_b$, so that, from Equation 4.8, trees with higher $A_t$ have higher $g_{bt}$ under the same wind conditions.

Equations for lines fitted to $g_{bt}$ data from each tree are plotted in Fig. 4.9 and given in Table 4.2. Each has the form $g_{bt} = c+bu^z$ and, in each case, the value of $z$ is between 0.5 and 0.8, thus lying between the value of 0.5 expected for laminar boundary layers and 0.8 expected for turbulent boundary layers (Schuepp, 1993).

**Table 4.2:** Equations relating wind speed ($u$) to summed leaf boundary layer conductances for tree crowns ($g_{bt}$) or bulk aerodynamic conductances ($g_a$) for *Azadirachta indica* trees in windbreaks at Sadoré. Heated leaf-replica pairs were used to measure $g_{bt}$ and the hanging-tree method was used to measure $g_a$.

| Year | Tree Label | Measurement Period (DOY) | Equation | r$^2$ | Equation no. |
|---|---|---|---|---|---|
| 1992 | O92 | 277-293 | $g_{bt} = 0.282 + 1.073\,u^{0.599}$ | 0.73 | (4.9) |
| 1993 | A93 | 114-126 | $g_{bt} = 0.299 + 0.287\,u^{0.658}$ | 0.60 | (4.10) |
| | J93 | 193-203 | $g_{bt} = 0.417 + 0.501\,u^{0.726}$ | 0.75 | (4.11) |
| | S93 | 260-271 | $g_{bt} = 0.522 + 1.606\,u^{0.554}$ | 0.67 | (4.12) |
| 1993 | HT1 | 284 | $g_a = 0.187 + 0.226\,u^{1.131}$ | 0.58 | (4.13) |
| | HT2 | 287 | | | |

### **4.4.4** *Bulk aerodynamic conductances for tree crowns*

One set of observations of tree mass, temperatures and wind speed made with the hanging-tree technique is shown in Fig. 4.10. Teklehaimanot and Jarvis (1991) observed that the surface temperature of the tree declined following wetting until approximately equal to the wet bulb temperature and defined the end of the period during which the tree crown was saturated as the point in time when the surface temperature of the crown began to climb above the wet bulb temperature. Figure 4.10 shows that, for the measurements reported here, the surface temperature of the crown declined only to within approximately 3 °C of the wet bulb temperature measured above the tree with an aspirated psychrometer. It is possible that this occurred because the foliage of the trees was not properly wetted. Visual inspection of the trees showed, however, that the tree crowns were thoroughly soaked during spraying and so it is more probable that the differences in temperature between the wet bulb of the psychrometer and the wet tree crowns resulted from large radiation loads on the trees, because both days on which measurements were made were clear and sunny. Values of $g_a$ were only calculated, consequently, for periods after drainage from the trees became negligible during which the plot of the surface temperature of the crown remained approximately parallel to the plot of the wet bulb temperature. As a result of high atmospheric vapour pressure deficits (1.8-4.5 kPa) on the days when measurements were made, this period usually lasted for only 1 to 5 min each time the trees were wetted.

Values of $g_a$ determined on both Tree HT1 and Tree HT2 during these periods are plotted in Fig. 4.11. Differences among observations arising from, for example, changes in wind direction or the dimensions and leaf areas of the two trees are not apparent. Parameters for equations relating $u$ and $g_a$ for each tree were not significantly different ($P<0.05$) and so a single equation for data from both trees is given in Table 4.2. This equation shows that the relationship between $g_a$ and $u$ is almost linear.

Also plotted in Fig. 4.11 are the $g_{bt}$ data measured for Tree S93 and, at any particular $u$, there are large differences between values of $g_{bt}$ for this tree and values of $g_a$. Tree S93 had a higher $A_t$ than either Tree HT1 or Tree HT2 (Table 4.1), and this suggests, from Equation 4.8, that aerodynamic conductances for Tree S93 should be higher. The differences between the values of $g_{bt}$ measured using heated leaf-replica pairs and values of $g_a$ measured using the hanging-tree technique are, however, too large to be accounted for solely by differences in the leaf areas of the trees used in each study. It can be concluded, therefore, that $g_{bt}$ and $g_a$ are not estimates of the same quantity. Two possible reasons for this are: (1) values of $g_b$ for all leaves in each layer of the tree crown were given equal

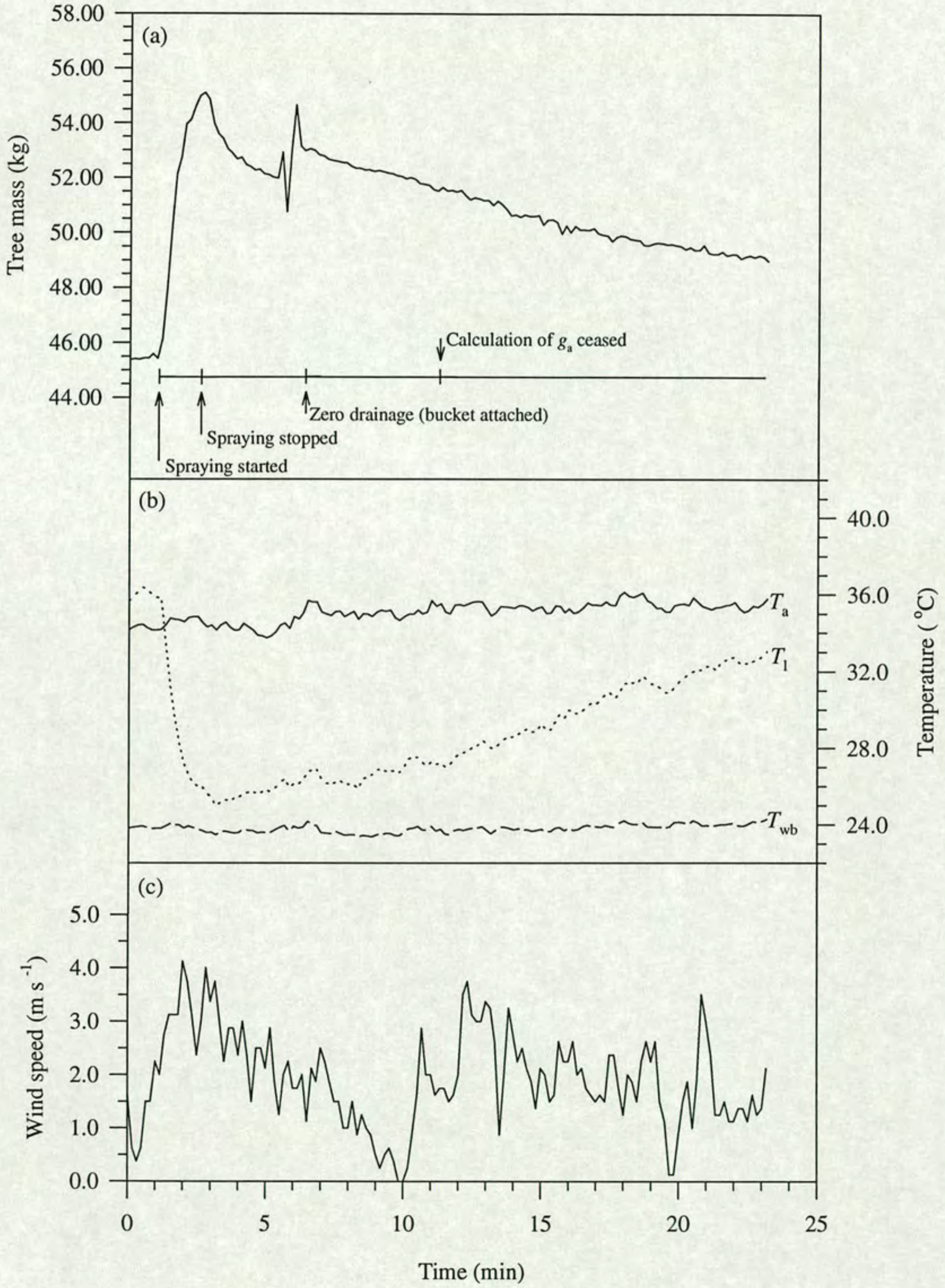


**Figure 4.10:** Data from one observation period of the hanging-tree experiment, showing (a) the mass of the wetted tree; (b) dry bulb temperature ($T_a$), wet bulb temperature ($T_{wb}$) and mean leaf temperature of the tree crown ($T_l$); and (c) wind speed at the top of the windbreak. The large perturbation in the line for tree weight occurred when a bucket was attached to the bottom of the excised tree trunk to collect run off from the trunk when dripping from the foliage had ceased.

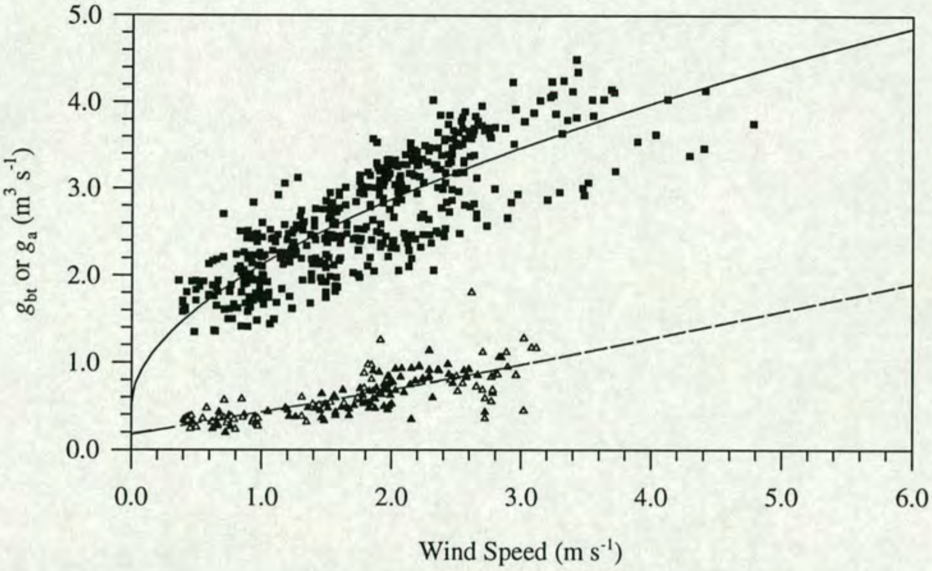


**Figure 4.11:** Dependence of bulk aerodynamic conductance to heat transfer ($g_a$) on wind speed for two trees (▲ and △) of *Azadirachta indica* in windbreaks, as measured using the hanging-tree technique, and a plot of the fitted equation for $g_a$ in Table 4.2 (– – –). The fitted equation for total leaf boundary layer conductance ($g_{bt}$) for Tree S93 (———) and measured values (■) are shown for comparison.

weighting when boundary layer conductances were scaled up from leaf to tree crown using Equation 4.8, and this may be incorrect; and (2) $g_{bt}$ and $g_a$ may be conductances for different portions of the pathway between leaf surfaces and the bulk air overlying the tree.

### **4.4.5** *Scaling up boundary layer conductances from leaf to crown*

McNaughton (1994) presented equations for aggregating boundary layer conductances over heterogeneous surfaces and demonstrated analytically that when scaling boundary layer conductances up from finer to coarser scales, it is necessary to weight the conductance for each unit at the finer scale by available energy if energy fluxes at the finer scale are to be conserved at the coarser scale. Thus, when extrapolating from boundary layer conductances for individual leaves to the bulk aerodynamic conductance for a tree crown, each conductance must be weighted by net radiation received by each leaf, so that leaves supporting larger energy fluxes contribute more to the aggregated conductance. Consequently, when boundary layer conductances are aggregated using Equation 4.8, conductances for leaves receiving more than the average net radiation are under-represented in the summed conductance for the tree crown and sheltered leaves that receive less than the average net radiation are over-represented.

If values of $g_b$ are to be weighted properly, therefore, when deriving values of $g_{bt}$, sheltered leaves towards the centre of the tree crown should be given a smaller weighting than they are given in Equation 4.8 and leaves near the outside of the crown should be given a larger weighting. Sheltered leaves tend to both receive less net radiation and have lower boundary layer conductances, while well-illuminated leaves near the outside of the crown are more exposed to atmospheric motions and so tend to have higher boundary layer conductances. Thus, if the weighting given to values of $g_b$ in Equation 4.8 is changed to reflect the contribution of each leaf to fluxes of energy from the crown, the representation of higher values of $g_b$ should increase and the representation of lower values of $g_b$ should decrease, so that values of the summed boundary layer conductance for the tree ($g_{bt}$) should be higher than found from Equation 4.8. This agrees with McNaughton's (1994) argument that, when heavier weighting is given to the conductances for sunlit than shaded leaves, aggregated boundary layer conductances for canopies will be higher than when calculated as the simple parallel sum of the component conductances.

Values of the bulk aerodynamic conductance for tree crowns ($g_a$) determined using the hanging-tree technique were derived from fluxes of water vapour measured at the (coarser) scale of the tree crown. Consequently, the contributions to $g_a$ of the boundary layer conductances for individual leaves are implicitly weighted by the proportion of the total flux of water vapour supported by each leaf in the crown. The flux of water vapour from each leaf is dependent on the net radiation received by the leaf, particularly at low wind speeds, and so $g_a$ should be equivalent to $g_{bt}$ when values of $g_b$ for individual leaves are properly weighted by net radiation. From McNaughton's (1994) arguments $g_a$ would be expected to be higher than values of $g_{bt}$ determined without weighting conductances by net radiation, using Equation 4.8. It is clear from Figure 4.11, however, that values of $g_a$ were, in fact, lower than values of $g_{bt}$ and so the weighting given to values of $g_b$ in Equation 4.8 cannot be the only cause of the large disparities found between $g_a$ and $g_{bt}$.

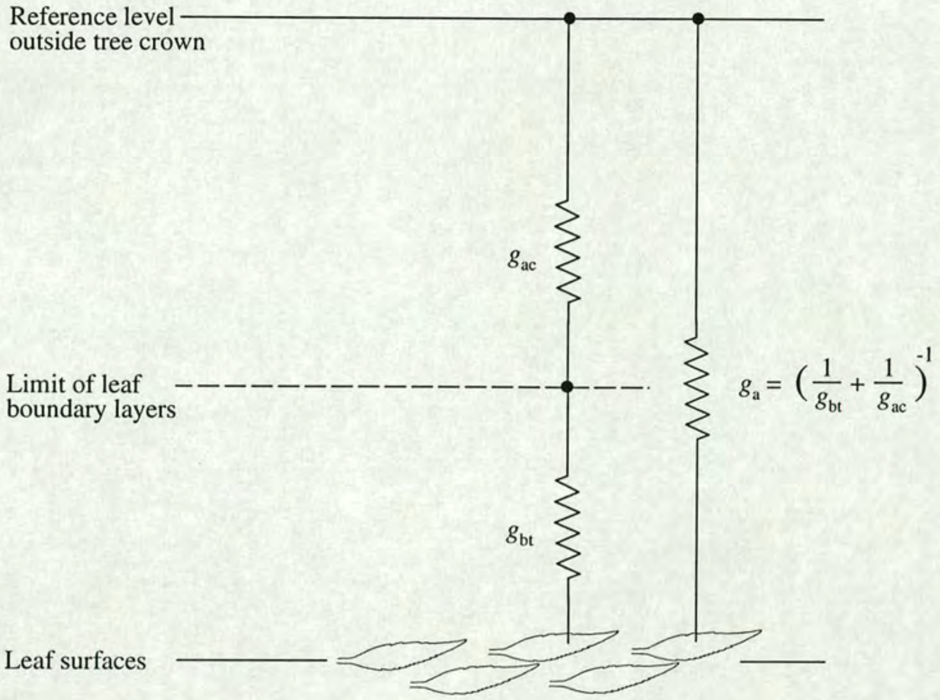


**Figure 4.12:** Electrical analogue illustrating the relationship between total leaf boundary layer conductance ($g_{bt}$) and bulk aerodynamic conductance ($g_a$) for tree crowns. Differences between them result from the conductance for transport between the edge of the leaf boundary layers and the reference level outside the crown ($g_{ac}$).

### **4.4.6** *Conductance through the windbreak canopy*

The differences in magnitude between $g_{bt}$ and $g_a$ may also have occurred because each represents the conductance for convective heat transfer between leaf surfaces and a different point in the pathway between leaves and overlying air. Values of $g_{bt}$ are conductances (integrated over the tree crown) for transfer between the leaf surface and the limit of the leaf boundary layer, which occurs within only a few millimetres of the leaf surface (Schuepp, 1993). In contrast, $g_a$ values are conductances for transfer between the surface of the tree crown and the position outside the crown where the reference value of ambient vapour pressure and temperature were measured. The path length for $g_a$ is, therefore, of the order of metres rather than millimetres, as is the case for $g_{bt}$, so that values of $g_a$ should be expected to be lower than values of $g_{bt}$, as observed. Accordingly, $g_{bt}$ should be regarded as a component of $g_a$, with the difference between them resulting from transport through the air within the tree crown between the limits of the leaf boundary layers and the reference height, as illustrated in Fig. 4.12. Using an electrical analogue, the conductance ($g_{ac}$) for this pathway is thus in series with $g_{bt}$, so that $g_a$ is given by their series sum:

$$\frac{1}{g_a} = \frac{1}{g_{ac}} + \frac{1}{g_{bt}}. \tag{4.14}$$

Thus, $g_{ac}$ is analogous to the "within-canopy" aerodynamic conductances included in schemes describing total aerodynamic conductances for plant canopies by L'homme (1988a, 1988b, 1991) and Ham and Heilman (1991) and is similar to the "turbulent conductance" defined by Finnigan and Raupach (1987) as mediating transport between the outer limit of the leaf boundary layer and the top of the canopy. Although Finnigan and Raupach (1987) comment that turbulent conductances can only be evaluated by solving complex models of turbulent transport within plant canopies, the data reported here suggest that within-canopy aerodynamic conductances can be explored by using heated leaf-replica pairs and the hanging-tree technique in tandem.

### **4.4.7** *Correction of values of* $g_{bt}$ *to estimate* $g_a$

The differences between $g_{bt}$ and $g_a$ demonstrate that bulk aerodynamic conductances for tree crowns cannot be derived directly from measurements of boundary layer conductances for leaves. Values of $g_a$ can only be derived from measured values of $g_{bt}$ if a correction is made to account for: (1) errors in the weighting given to values of $g_b$ for leaves from different parts of the tree crown when calculating $g_{bt}$; and (2) the conductance for transfer between the limits of the leaf boundary layers and the air outside the crown. The magnitude of the correction required as a result of errors in the weighting of values of $g_b$ could be ascertained by using models of light interception, such as the model developed by Wang and Jarvis (1990), to calculate the distribution within the tree crown of net radiation absorption. Corrections for the difference in path length between $g_a$ and $g_{bt}$ can be determined by estimating values of $g_{ac}$ by difference on the basis of Equation 4.14.

Values of $g_{ac}$ estimated in this way are not purely aerodynamic conductances for transfer between leaf boundary layers and overlying air, however, because they also contain effects resulting from the errors in $g_{bt}$ caused by the distribution of net radiation in the tree crown. Hence, values of $g_{ac}$ estimated by difference include effects of both the distribution of net radiation in the crown and the difference in path length between $g_a$ and $g_{bt}$. The effect on $g_{ac}$ of weighting leaf boundary layer conductances for net radiation is probably small, however, relative to the effect of the difference in path length between $g_a$ and $g_{bt}$, because $g_a$ was observed to be lower than $g_{bt}$ rather than higher, as would result from errors in the weighting of values of $g_b$. Thus, the magnitude of $g_{ac}$, when estimated by difference on the basis of Equation 4.14, is largely determined by the aerodynamic conductance for transfer between the limits of the leaf boundary layers and the air outside the tree crown.

If values of $g_{ac}$ are used to estimate values of $g_a$ from measured values of $g_{bt}$, large errors will not occur provided that the crowns of the trees used to derive $g_{ac}$ and the trees used to measure $g_{bt}$ have a similar structure. In such cases, the weighting of leaf boundary layer conductances for net radiation and the path lengths and distribution of path lengths between the limits of the leaf boundary layers and air outside the tree crown are similar for each tree, so that errors caused by extrapolating $g_{ac}$ from one tree to another are probably small. Thus, values of $g_a$ for the *A. indica* trees in windbreaks at Sadoré can be estimated by correcting measured values of $g_{bt}$ using a suitable estimate of $g_{ac}$.

### **4.4.8** *Estimation of $g_{ac}$*

The magnitude of $g_{ac}$ can be estimated by comparing fitted curves for $g_{bt}$ and $g_a$ for two tree crowns of similar structure and leaf area. Tree S93 and Tree HT1 had similar dimensions (Table 4.1) and were located within 10 m of each other in the same windbreak. A comparison of the aerodynamic conductances measured for these trees can be made by scaling $g_{bt}$ for Tree S93 to the leaf area for Tree HT1 on the basis of Equation 4.8. This is accomplished by multiplying values of $g_{bt}$ calculated using Equation 4.12 by the ratio, $f_l$, of the values of $A_t$ for Tree HT1 and Tree S93, where $f_l$=42.1/55.8 (Table 4.1). By combining Equations 4.12, 4.13 and 4.14, $g_{ac}$ can then be estimated using

$$\frac{1}{g_{ac}} = (0.187 + 0.226u^{1.131})^{-1} - f_l(0.522 + 1.606u^{0.554})^{-1}. \qquad (4.15)$$

A plot of $g_{ac}$ against $u$, determined using Equation 4.15, is shown in Fig. 4.13a. Also shown in Fig. 4.13a, for comparison, is a plot of $g_a$ for Tree HT1 determined from Equation 4.13 and a plot of $g_{bt}$ for Tree HT1 estimated by scaling Equation 4.12 by $f_l$. The simple additive relationship between the reciprocals of the conductances (Equation 4.14) is shown in Fig. 4.13b.

Values of $g_a$ for *A. indica* trees in windbreaks at the site can thus be estimated using Equation 4.14 from measurements of $g_{bt}$ made using heated leaf-replica pairs and estimates of $g_{ac}$ made using Equation 4.15. When $g_a$ is estimated in this way, it can be used in Equation 4.1 to calculate sensible heat fluxes for *A. indica* trees in windbreaks at the site, but there is then an implicit assumption that the relationship between $g_{ac}$ and wind speed depicted in Fig. 4.13a is the same for each of the tree crowns studied, regardless of their dimensions or leaf areas.

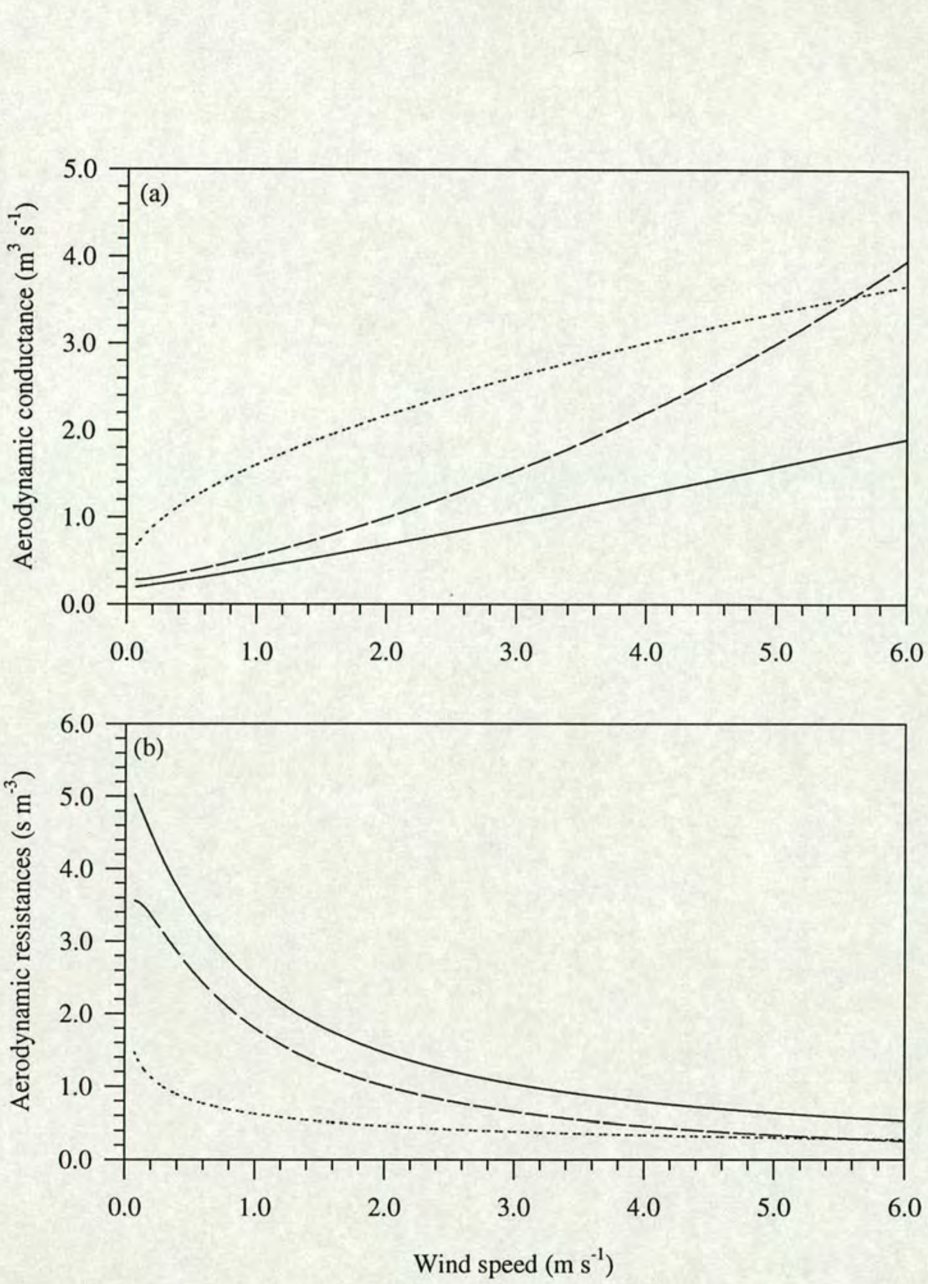


**Figure 4.13:** (a) Dependence on wind speed of: the bulk aerodynamic conductance ($g_a$) (———), as given by Equation 4.13; the aerodynamic conductance for transfer between the limits of the leaf boundary layers and the air outside the crown ($g_{ac}$) (– – –), from Equation 4.15; and the total leaf boundary layer conductance ($g_{bt}$) (·········), estimated by scaling Equation 4.12 by $f_l$ (see text), for Tree HT1 in a windbreak of *Azadirachta indica* trees at Sadoré. (b) The equivalent aerodynamic resistances for these conductances, calculated as the inverse of each conductance.

Previously, others who have investigated transfer of heat and mass from hedgerows or isolated trees (Landsberg *et al.*, 1975; Butler, 1976; Thorpe, 1978; Landsberg and McMurtrie, 1984; Green, 1993) have estimated aerodynamic conductances using an empirical equation for the boundary layer conductances of mutually-sheltered leaves that Landsberg and Powell (1973) developed from measurements in a wind tunnel on an artificial tree. The results described here show that it is not necessary to rely on this equation in such studies because aerodynamic conductances for isolated trees and trees in hedgerows or windbreaks can be measured directly.

## 4.5 Conclusions

Boundary layer conductances for model leaflets of *A. indica* measured in the wind tunnel broadly concurred with expectations based on published results of experiments with model leaves. Values were enhanced above theoretical values for smooth, flat plates but were approximately proportional to $u^{0.5}$ at low wind speeds and to $u^{0.8}$ when boundary layers were turbulent; boundary layer conductances for leaves were similarly dependent on $u$ when measured inside the crowns of trees in windbreaks. However, the relationship between $u$ and bulk aerodynamic conductances for similar tree crowns measured with the hanging-tree technique was almost linear. Bulk aerodynamic conductances were also much lower than leaf boundary layer conductances summed for tree crowns with similar leaf areas.

The hanging-tree technique and heated leaf-replica pairs thus measure different, but related, components of aerodynamic conductances for whole trees. Measurements made with heated leaf-replica pairs quantify the conductance for heat transfer between the surface of a leaf and the limit of the leaf boundary layer, while measurements made with the hanging-tree method quantify the conductance for transfer between the surfaces of leaves in the tree crown and a reference level outside the crown. Differences between summed leaf boundary layer conductances for whole trees and bulk aerodynamic conductances largely result, consequently, from the conductance through air within the tree crown between the limits of the leaf boundary layers and the reference level, although errors in the weighting given to boundary layer conductances for individual leaves were probably also responsible for minor components of these differences under the conditions of this study. Use of the hanging-tree technique and heated leaf-replica pairs together thus provides a much less complex way of estimating conductances for the transfer of heat through air within plant canopies than was discussed by Finnigan and Raupach (1987).

At sites where trees are distributed sparsely or non-homogeneously across the landscape, as is usually the case for agroforestry in semi-arid zones, for example, the conductance parameter in Equation 4.1 cannot be estimated for individual tree crowns from theory because changes in surface characteristics occur over distances that are too short for the airstream to adjust fully to the surface. The method developed by Teklehaimanot and Jarvis (1991) for directly estimating bulk aerodynamic conductances for the crowns of individual trees provides an alternative to theory at such sites, but their technique requires destruction of trees and so it is often not possible to make many measurements using the method at agroforestry trials where removal of trees can alter the nature of the site. Consequently, the approach used here, where measurements of leaf boundary layer conductances on many trees are combined with measurements of bulk aerodynamic conductances on only a few trees, is ideally suited for use in experiments in agroforestry for which aerodynamic conductances for individual tree crowns are needed.

Thus, the procedures used in this study should be particularly useful to researchers examining energy budgets of tree crowns and canopies of groups of trees in agroforestry, horticulture or other settings where trees are isolated or do not form a closed canopy. In experiments of this type, sensible heat fluxes can be estimated using Equation 4.1 on the basis of aerodynamic conductances measured using the methods employed here and measurements of differences in temperature between the foliage of the trees and ambient air. Energy budgets of windbreaks, hedgerows or individual trees have not been widely studied in the past because the geometry of trees in these configurations causes difficulties in quantifying the different components of the energy budget. The means of measuring sensible heat fluxes for individual trees suggested by the results of this study should consequently encourage research into the energy budgets of trees in stands where they are mixed with other types of vegetation. Such research is particularly desirable in agroforestry because it will help to advance our understanding of the physiological mechanisms driving competition between trees and adjacent crops.

# Chapter 5

## Energy Budgets of Windbreak Canopies in the Sahel

### 5.1 Introduction

Reductions in wind speeds behind windbreaks result in changes in microclimate that have important implications for water use by sheltered crops. Higher daytime air temperatures and vapour pressures and steeper vertical gradients in temperature and vapour pressure have been observed when microclimate behind windbreaks and nearby, unsheltered fields have been compared (Brown and Rosenberg, 1972; Skidmore *et al.*, 1972; Miller *et al.*, 1973; Rosenberg *et al.*. 1983). These observations result from reduced turbulent transport in a "quiet zone" behind windbreaks where mean wind speeds are reduced and eddies are smaller in size and less energetic than in the open, so that heat and vapour tend to accumulate close to the surface (McNaughton, 1988; 1989a). The extent of the quiet zone can vary, but it often extends into the field in the lee of a windbreak to a distance in the order of eight times the height of the windbreak (McNaughton, 1988; Brenner, 1991). A crop growing in the quiet zone is thus isolated from air in the overlying mixed layer by a layer of slow-moving air that tends to prevent incursions of air from overhead from reaching the crop surface.

Advection enhances evapotranspiration from vegetated surfaces when air upwind is warmer and drier than air at the surface because turbulent motions in the atmosphere then bring warm, dry air to the vegetation and prevent equilibration between the atmosphere and the fluxes of heat and vapour from the surface (McNaughton, 1976b; McNaughton and Jarvis, 1983). The reduction in turbulent transport in the quiet zone behind a windbreak tends to prevent such atmospheric motions from reaching crops growing in the lee of windbreaks, so that advective enhancement of evapotranspiration is reduced behind windbreaks (McNaughton, 1983). Turbulent entrainment of drier air from above the planetary boundary layer overlying a region similarly prevents equilibration between the atmosphere and the surface (McNaughton, 1989b; McNaughton and Spriggs, 1989) and so the reduction in turbulent transport behind windbreaks protects crops in their lee from increased evaporative demand resulting from the combined effects of advection and turbulent entrainment.

Where surfaces are able to equilibrate with overlying air, for example where vegetation is homogeneous over a large area and advection is negligible or where an inversion cap above the surface suppresses turbulent mixing, it can be shown theoretically that evaporation approaches an equilibrium rate which depends on radiation absorbed and temperature (McNaughton, 1976a; McNaughton and Jarvis, 1983). Thus, McNaughton (1983, 1988) argued that evapotranspiration in the quiet zone behind windbreaks should tend more towards the equilibrium rate than in unsheltered fields and others have observed evapotranspiration from windbreak-sheltered fruit orchards to approach the equilibrium rate closely (Judd and McAneney, 1984; McAneney *et al.*, 1992).

The microclimate in which trees in windbreaks must grow contrasts sharply with that in the quiet zone in their lee. While turbulent transport to a sheltered crop is suppressed, trees in a windbreak immediately adjacent to the crop are openly exposed to turbulent motions in the atmosphere because windbreaks are taller than the crop and usually only one or two trees in width. There is no possibility for the humidity of air passing over and through the foliage of windbreaks to equilibrate with transpiration from the trees and so advection and entrainment may substantially enhance transpiration from trees in windbreaks. In semi-arid regions such as the Sahel, where the availability of water can be an important constraint on plant production (Sivakumar and Wallace, 1991), such enhancement of transpiration from windbreak trees may influence water budgets for windbreak systems and competitive interactions among component species. The objective of the present study was, therefore, to determine how radiant energy is dissipated by windbreak canopies in the Sahel in order to quantify the effects of advection and entrainment on transpiration by trees in windbreaks. Energy budgets of windbreak canopies were measured, consequently, at four different times of year at a location in southern Niger.

## 5.2 Theory

### **5.2.1** *Canopy energy budgets*

The energy budget for a plant canopy can be written as

$$R_n = \lambda E + H + \Delta S, \tag{5.1}$$

where $R_n$ is net radiation absorbed by the canopy, $E$ is evaporation and $\lambda E$ is latent heat flux, $H$ is sensible heat flux and $\Delta S$ is the change in heat storage by the canopy. Equation 5.1 differs from expressions of energy budgets for extensive land surfaces in that there is no term for ground heat flux because it applies only to absorption and dissipation of energy by the leaves, branches and air within the three-dimensional volume filled by a plant canopy. The components of Equation 5.1 should consequently be quantified as total energy fluxes for the canopy volume, unless the canopy under study is extensive in any dimension.

Canopies of windbreaks are extensive along their length and so exchange of energy between windbreaks and the environment can be expressed per unit windbreak length.

### 5.2.2 *Equilibrium evaporation*

For the windbreak energy budget expressed by Equation 5.1, available energy ($A$) is given by $A = (R_n - \Delta S)$. At equilibrium, $A$ is partitioned between sensible and latent heat in the constant ratio $\gamma/s$ (McNaughton, 1976a), where $\gamma$ is the psychrometric constant and $s$ is the slope of the saturation vapour pressure curve at the surface temperature. When sensible and latent heat are added to the air in the mixed layer above the vegetation in this ratio, vapour pressure deficit is unchanged and equilibrates at a value, $D_{eq}$, given by (McNaughton and Jarvis, 1983)

$$D_{\mathrm{eq}} = \left(\frac{s}{s+\gamma}\right)\frac{\gamma A}{\rho_a c_p g_c}, \qquad (5.2)$$

where $\rho_a$ is the density of air, $c_p$ is the specific heat capacity of air at constant pressure and $g_c$ is the canopy conductance for the vegetation at the surface. Evapotranspiration for well-watered vegetation under these conditions depends on $A$ and temperature according to (McNaughton, 1976a)

$$\lambda E_{\mathrm{eq}} = \frac{s}{s+\gamma} A, \qquad (5.3)$$

where $E_{eq}$ is the equilibrium evaporation rate.

### 5.2.3 *Advection*

Where the atmosphere is not in equilibrium with vegetation, horizontal gradients in ambient vapour pressure deficit ($D_a$) arise and advection occurs because atmospheric motions continually transport air with a non-equilibrium vapour pressure deficit to the surface (McNaughton, 1976b). Evapotranspiration is said to be advectively depressed if the air arriving at the surface has a value of $D_a < D_{eq}$ because $E$ is depressed below $E_{eq}$, whereas, if the air arriving at the surface has a value of $D_a > D_{eq}$, $E$ is enhanced above $E_{eq}$ and evapotranspiration from the surface is advectively enhanced (McNaughton, 1976b; McNaughton and Jarvis, 1983).

Advection is important when air passes over a boundary between surfaces with differing types of vegetation because a new equilibrium must then be established between the atmosphere and conditions at the surface. Where the contrast between the two surfaces is large, as, for example, at the boundary of an irrigated crop surrounded by desert, air blowing over the vegetation must travel distances of several hundred metres before equilibrating with the surface (Davenport and Hudson, 1967). Advection can therefore influence $E$ for considerable distances downwind of a boundary between vegetation types, although the influence of advection on transpiration in such circumstances can be mitigated by feedbacks between the atmosphere and $g_c$ where, for example, advective enhancement of transpiration is reduced by stomatal closure close to the upwind boundary of a vegetated surface (Kroon and de Bruin, 1993; McAneney *et al.*, 1994).

### **5.2.4** *Turbulent entrainment*

$E$ does not often approach $E_{eq}$, even for very extensive areas of vegetation because turbulent entrainment of drier, warmer air from above the planetary boundary layer tends to prevent complete equilibration between the surface and overlying air (McNaughton, 1989b; McNaughton and Spriggs, 1989). If air entrained into the mixed layer overlying vegetation has a value of $D_a \neq D_{eq}$, air arriving at the surface will tend to enhance or depress $E$ relative to $E_{eq}$ and have similar consequences for surface fluxes as advection (McNaughton and Spriggs, 1986).

As discussed by McNaughton and Spriggs (1989), the influence of entrainment on $E$ for horizontally-extensive surfaces can be expressed using a factor $\alpha$, calculated as $E/E_{eq}$. The factor $\alpha$ was originally argued by Priestley and Taylor (1972) to have a value of 1.26 for a well-watered vegetated surface, but $\alpha$ varies with the vapour pressure deficit of entrained air (McNaughton and Spriggs, 1986) and is strongly dependent on $g_c$, so that values of <1.0 can occur for surfaces with low conductances (McNaughton and Spriggs, 1989).

### **5.2.5** *Exchange flux*

Arrival of air with a non-equilibrium $D_a$ at the surface, whether as a result of advection or turbulent entrainment, causes partitioning of available energy between sensible and latent heat fluxes to shift from the ratio $\gamma/s$ which prevails at equilibrium. This shift occurs without the net addition of any energy and results from the exchange of energy between sensible and latent heat at the surface (McNaughton, 1976b). When air arriving at the surface has a value of $D_a > D_{eq}$, sensible heat in the air is converted to latent heat and $E$ is driven above $E_{eq}$, whereas, conversely, when air transported to the surface is more moist than $D_{eq}$, latent heat is exchanged for sensible heat and $E$ is depressed below $E_{eq}$. The effects of advection and turbulent entrainment on $\lambda E$ can consequently be quantified as the deviation of $\lambda E$ from $\lambda E_{eq}$ (McNaughton, 1983):

$$X = \lambda E_{\mathrm{eq}} - \lambda E, \qquad (5.4)$$

where $X$ is the exchange flux and represents the amount of energy exchanged between sensible and latent heat at the surface. $X$ is positive when $E$ is depressed by advection and entrainment and negative when $E$ is enhanced. The ratio $-X/\lambda E$ consequently represents the proportion of $E$ driven by the transport of dry air to the surface as a result of advection and entrainment. For comparison, $-X/\lambda E$ can be converted to $\alpha$ using $\alpha=(1+X/\lambda E)^{-1}$.

### 5.3 Measurement principles

Each of the components of the canopy energy budget (Equation 5.1) can be measured independently in the following ways.

#### 5.3.1 *Net radiation*

$R_n$ can be determined using the method, described by Thorpe (1978), in which an array of eight linear net radiometers is mounted at equally-spaced positions around the surface of a notional cylinder enclosing the windbreak canopy (Fig 5.1a). The radiometers are oriented with their long axes parallel to the windbreak and with the surfaces of the sensors tangential to the surface of the imaginary cylinder. $R_n$ is then calculated by integrating net radiation around the cylinder using (Thorpe, 1978)

$$R_n = 2\pi r_c \overline{R_n}, \qquad (5.5)$$

where $r_c$ is the radius of the notional cylinder and $\overline{R_n}$ is the mean value (per unit area) of net radiation across all eight sensors.

#### 5.3.2 *Latent heat flux*

$\lambda E$ was estimated from measurements of transpiration from a single tree inside the net radiometer array, made using the heat-pulse technique to determine the rate of sap flow in the trunk of the tree. This technique uses short pulses of heat as a tracer for determining the velocity of sap rising up woody stems, with sap velocities derived from the upward velocity of heat pulses by accounting for the thermal properties of moist wood according to Marshall (1958) and for thermal inhomogeneities caused by the implantation of sensors into the stems according to Swanson and Whitfield (1981). In the method described by Edwards and Warwick (1984), sap velocities are measured at a different depth below the cambium of the tree stem at each of four evenly-spaced positions around the circumference of the stem using sets of heat-pulse probes. Each set of probes, comprising a heater and two

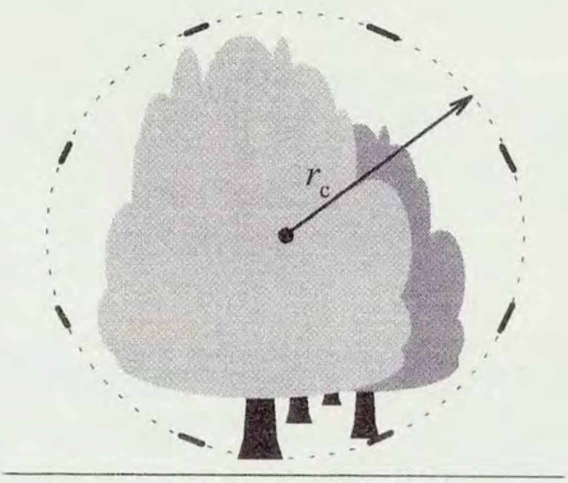


**Figure 5.1a:** Schematic diagram showing a cross-sectional view of a double-row windbreak enclosed in an array of eight linear net radiometers ( —) mounted at equally-spaced positions around a notional cylinder of radius $r_c$. Net radiation absorbed per unit length of windbreak is calculated by integrating the output from all eight sensors around the surface of the cylinder using Equation 5.5. (Adapted from Thorpe (1978)).

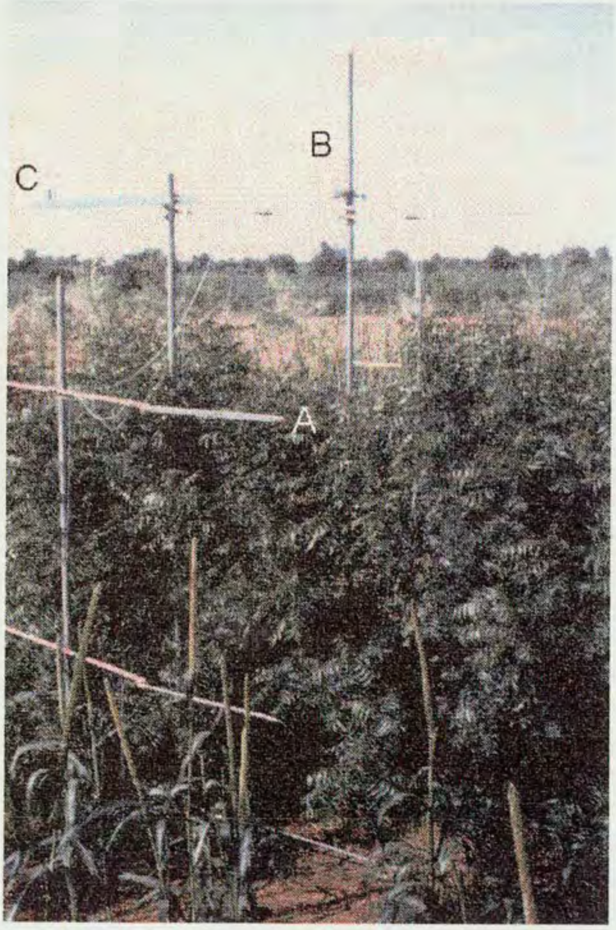


**Figure 5.1b:** Instruments deployed in the field to measure the energy budget of a windbreak of *Azadirachta indica* trees. Eight linear net radiometers (A) were arranged in an array surrounding the windbreak and a psychrometer (B) and anemometer (C) were used to measure reference temperatures, vapour pressures and wind speeds.

probes containing thermistors, is installed into parallel holes drilled radially into the stem at each position. Sap flux densities are calculated from the measured sap velocities and volume flow rates of sap are calculated from the integral over the sapwood cross-section of a second-order least squares regression equation fitted to the sap flux density profile between the the cambium and the heartwood (Edwards and Warwick, 1984; Green and Clothier, 1988) or, where this results in extrapolation to unrealistically high values of sap flux, from the integral of a step function of sap flux density with radial depth (Hatton *et al.*, 1990). Thus, transpiration per tree ($E_t$), expressed as a mass flow rate, is calculated for the tree studied using (Green and Clothier, 1988; Green, 1993)

$$E_t = 2\pi\rho_w \int_h^R r_d \, q_v'(r_d) \; \mathrm{d}r_d \ , \tag{5.6}$$

where $\rho_w$ is the density of water and $q_v'(r_d)$ is volumetric sap flux density as a function of radial depth, $r_d$, in a trunk with a radius at the cambium of $R$ and a radius for the heartwood of $h$.

$\lambda E$ is then calculated from $E_t$ using

$$\lambda E = \lambda E_t f_{tw} \ , \tag{5.7}$$

where $f_{tw}$ is a scaling factor that converts transpiration per tree to transpiration per unit length of windbreak on the basis of leaf area. The factor $f_{tw}$ is derived from the linear projected leaf area density for the windbreak ($L_w$) (ie. projected leaf area per unit length of windbreak) inside the net radiometer array and the projected leaf area of the tree ($A_t$) used to measure $E_t$ using

$$f_{tw} = \frac{L_w}{A_t} \ . \tag{5.8}$$

### **5.3.3** *Sensible heat flux*

The equation for convective heat transfer (Monteith and Unsworth, 1990),

$$H = \rho_a c_p \left(T_s - T_a\right) g_a f_{tw} \ , \tag{5.9}$$

is used to estimate $H$, where ($T_s$-$T_a$) is the difference in temperature between the surface of the canopy and ambient air at reference height and $g_a$ is the bulk aerodynamic conductance (on a per tree basis) of the tree enclosed by the net radiometer array.

### **5.3.4** *Canopy heat storage*

$\Delta S$ can be approximated from

$$\Delta S = m_{\mathrm{t}} c_{\mathrm{sm}} \left( \frac{\Delta T_{\mathrm{w}}}{\Delta t} \right) n_{\mathrm{t}} \ , \tag{5.10}$$

which is a simplified estimate of heat storage within the woody mass of the canopy (Aston, 1985) and assumes that heat storage in the leaves and air within the canopy is negligible. $\Delta T_{\mathrm{w}}$ is the change in wood temperature over the time interval $\Delta t$, $m_{\mathrm{t}}$ is the fresh mass of the tree, $c_{\mathrm{sm}}$ is the specific heat capacity of moist wood and $n_{\mathrm{t}}$ is the number of trees per unit length of windbreak.

## **5.4 Experimental details**

### **5.4.1** *Site description*

Measurements were made on windbreaks of *Azadirachta indica* A. Juss. growing at the research farm of the ICRISAT Sahelian Centre at Sadoré (13°14'N, 2°16'E), about 45 km south of Niamey, the capital of Niger. The climate of this region is typically Sahelian, with most rain falling in a single, short rainy season between June and September. Mean annual rainfall at Niamey is 545 mm. Air temperatures during the dry season tend to be high, with monthly means for daily maximum temperatures ranging from 33 to 40 °C between October and May (Sivakumar *et al.*, 1993).

Windbreaks at the site were formed by double rows of alternately planted trees, with 1.5 m between rows and 3 m between trees in the same row. They were oriented north-south, were 50 m long and there was 30 m of cropland between parallel windbreaks. The windbreaks were managed as hedge windbreaks and so were pruned back to 2 m from a height of 4 to 5 m at the end of every dry season. Pearl millet (*Pennisetum glaucum* (L.) R. Br.) was grown between the windbreaks during the rainy season.

### **5.4.2** *Measurement periods*

The energy budget of a section of a single *A. indica* windbreak was measured during each of four periods in 1992 and 1993, with each period occurring during a different season of the year. The first set of measurements were made between DOY 277 and 293, 1992, during the early part of the dry season and the second set from DOY 114 to 126, 1993, during the late part of the dry season, before any rain had fallen in 1993. The final two periods of measurement took place in 1993 between DOY 193 and 203, in the middle of the rainy season, and then between DOY 260 and 271, near the end of the wet season.

### **5.4.3** *Instrumentation and data collection*

The linear net radiometers (Swissteco, Melbourne, Australia) used to measure $R_n$ had sensors that were 0.88 m in length. During each period of measurement, the radiometers, which were calibrated against two Fritschen-type domed net radiometers (Q5.5, REBS Inc., Seattle WA, USA.), were mounted in an array centred on the trunk of a tree (hereafter called the instrumented tree) in one row of the windbreak but enclosing the foliage of both rows, as shown in Fig. 5.1a and 5.1b. The radius of the net radiometer array was 2.0 m for DOY 193 to 203, 1993, and 2.25 m for all other periods of measurement.

The heat-pulse probes (HortResearch, Palmerston North, New Zealand) were installed in the trunk of the instrumented tree in order to determine $E_t$. Tests in the laboratory and in the field of the validity of sap flow rates measured in *A. indica* with the heat-pulse technique, using methods outlined by Green and Clothier (1988), showed that measured sap flow ($F_h$) needed to be corrected using

$$F_c = 1.62 F_h \ , \tag{5.11}$$

where $F_c$ is corrected sap flow. The methods used to derive Equation 5.11 and an explanation of the need for it are discussed in Appendix A.

Measurements of ($T_s$-$T_a$), required to estimate $H$ using Equation 5.9, were made using thermocouples, made from 0.2 mm diameter teflon-coated copper-constantan thermocouple wire (TC Ltd., Uxbridge, UK.), attached to five leaves in each of three horizontal layers of the crown of the instrumented tree using small pieces of porous surgical tape (Leuning and Foster, 1990). The thermocouples in each layer of the crown were connected in parallel with their reference junctions located at the dry bulb of an aspirated psychrometer (Allen *et al.*, 1994) mounted above the windbreak at a height of 4 m above the ground, so that mean leaf-air temperature difference was measured directly for each layer. Mean ($T_s$-$T_a$) for the entire crown was then calculated by weighting values of the leaf-air temperature difference for each layer of the tree crown by the proportion of leaf area in each layer.

Estimation of $H$ using Equation 5.9 also requires values of $g_a$ for the tree instrumented during each period of measurement. Leaf boundary layer conductances were measured at three locations in each of three layers of the crown of the instrumented tree using nine heated leaf-replica pairs (Leuning, 1989; Leuning and Foster, 1990; Brenner, 1991), as described in Chapter 4. Summed leaf boundary layer conductances ($g_{bt}$) for the crown of the instrumented tree were then calculated by assuming that boundary layer conductances for all individual leaves in a tree crown are conductances in parallel. The response of $g_{\mathrm{bt}}$ to wind speed at reference height was then modelled for each tree studied using non-linear regression. Values of $g_{\mathrm{a}}$ were finally derived from values of $g_{\mathrm{bt}}$, calculated from measured wind speeds, using

$$\frac{1}{g_{\mathrm{a}}}=\frac{1}{g_{\mathrm{bt}}}+\frac{1}{g_{\mathrm{ac}}}, \qquad (5.12)$$

where $g_{\mathrm{ac}}$ is the conductance for transfer between the leaf boundary layers and the reference level outside the tree crown (see Equation 4.15).

Measurements required to estimate $\Delta S$ were carried out only in the measurement period from DOY 277 to 293, 1992. $T_{\mathrm{w}}$ was measured using six copper-constantan thermocouples (0.2 mm diameter, TC Ltd., Uxbridge, UK.) embedded in wood 5-10 mm below the bark of the instrumented tree. The volume of wood in the tree was estimated from the lengths and diameters of the trunk and main branches and converted to $m_{\mathrm{t}}$ using a value of 1014 kg m$^{-3}$ for the bulk density of fresh *A. indica* wood, a value determined from samples of wood collected at the site using the method described by Edwards and Warwick (1984). The value of $c_{\mathrm{sm}}$ for *A. indica* wood at the site was estimated to be ≈2376 J kg$^{-1}$ K$^{-1}$ by weighting the specific heat capacities of woody matrix and water by their volume fractions, which were determined from samples of wood extracted from the tree (see Edwards and Warwick, 1984).

Reference values of air temperature, vapour pressure deficit and wind speed were measured using an aspirated psychrometer (Allen *et al.*, 1994) and a cup anemometer (A100R, Vector Instruments Ltd., Rhyl, UK.) mounted next to the windbreak at 4 m above the ground, as pictured in Fig. 5.1b. The heat-pulse data were recorded every 20 min using a heat-pulse logger (Custom HP1, HortResearch, Palmerston North, New Zealand) and all other data were logged at intervals of 30 s and averaged over 20 min using a 21X data logger and AM32 multiplexer (Campbell Scientific Ltd., Shepshed, UK.).

### **5.4.4** *Measurement of leaf area and estimation of* $f_{tw}$

At the end of each period of measurement, the crown of the instrumented tree was divided into three horizontal and three vertical sections using flagging tape to demarcate boundaries between sections. All leaves were then harvested and the projected leaf area for each section estimated as the product of the total dry mass and specific leaf area of leaves in each section. Specific leaf areas were calculated from the projected leaf area, measured using a leaf area meter (LI-3100, Li-Cor Inc., Lincoln NE, USA.), and dry

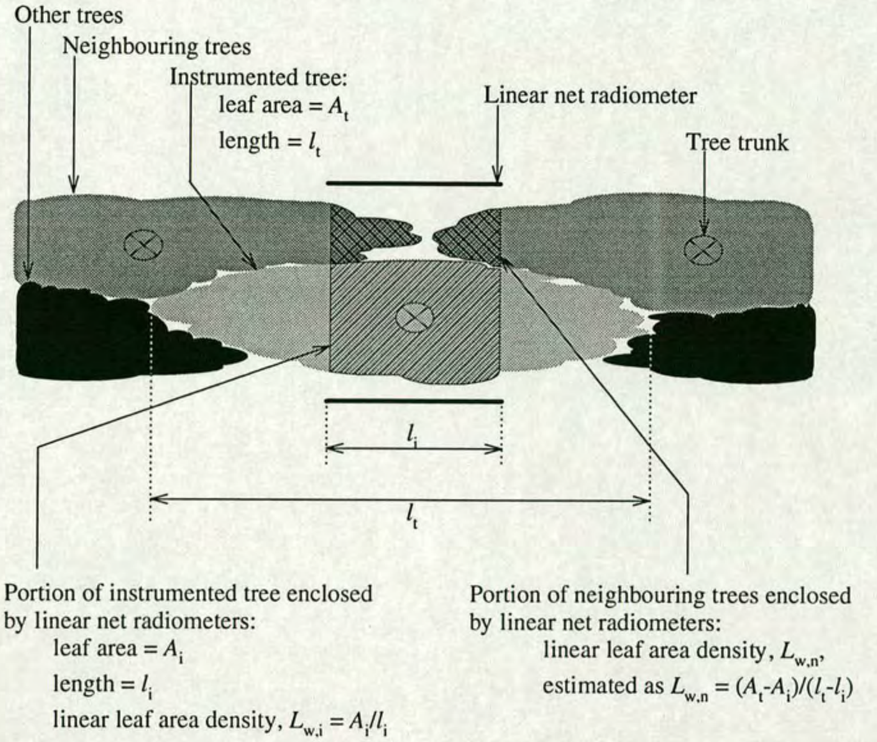


**Figure 5.2:** Schematic diagram showing a view from above of a double-row windbreak enclosed by an array of linear net radiometers centred on the trunk of a tree instrumented for the determination of the energy budget of the windbreak canopy. The linear leaf area density ($L_w$) of the portion of the canopy enclosed within the array is estimated as $L_w=L_{w,i}+L_{w,n}$, where $L_{w,i}$ and $L_{w,n}$ are the linear leaf area densities of the portions of the crowns of, respectively, the instrumented tree and neighbouring trees enclosed within the net radiometer array. $L_{w,i}$ is calculated from the leaf area in the central section of the instrumented tree and $L_{w,n}$ is estimated from the leaf area of the outer sections of the instrumented tree.

mass of a subsample of leaves harvested from each section. Total projected leaf area ($A_t$) for the tree was calculated by summing the leaf areas for the sections.

The value of $L_w$ used in Equation 5.8 to calculate $f_{tw}$ was estimated from leaf areas in the vertical sections of the crown. The net radiometer array enclosed foliage from both rows of the windbreak (Fig. 5.2) and so both the instrumented tree and neighbouring trees whose foliage impinged on the volume enclosed by the radiometers contributed to $L_w$. The component of $L_w$ contributed by the instrumented tree was estimated from the linear leaf area density of the vertical section at the centre of the tree crown ($L_{w,i}$), given by

$$L_{w,i} = \frac{A_i}{l_i} , \tag{5.13a}$$

where $A_i$ and $l_i$ are the leaf area and length of the vertical section at the centre of the instrumented tree, respectively. The linear leaf area density of the foliage of neighbouring trees ($L_{w,n}$) inside the net radiometer array was approximated from the leaf area of the instrumented tree outside the central vertical section (ie., $A_t$-$A_i$) using

$$L_{w,n} = \frac{A_t - A_i}{l_t - l_i} , \tag{5.13b}$$

where $l_t$ is the total length of the crown of the instrumented tree along its axis parallel to the windbreak. As illustrated in Fig. 5.2, $L_w$ was then calculated from

$$L_w = L_{w,i} + L_{w,n} . \tag{5.13c}$$

## 5.5 Results and discussion

### 5.5.1 *Net radiation*

Net radiation absorption per unit length of windbreak is plotted for two days in Fig. 5.3, together with concurrent measurements of net radiation in a horizontal plane ($R_{nc}$) over the millet crop adjacent to the windbreak. On DOY 197, 1993, large, rapid fluctuations in $R_{nc}$ occurred as a result of variability in incoming solar radiation caused by clouds passing over the site (Fig. 5.3a). These fluctuations are also apparent in the data for $R_n$ on the same day, demonstrating that the net radiometer array used to measure $R_n$ was sensitive to short-term changes in the radiation load on the windbreak canopy.

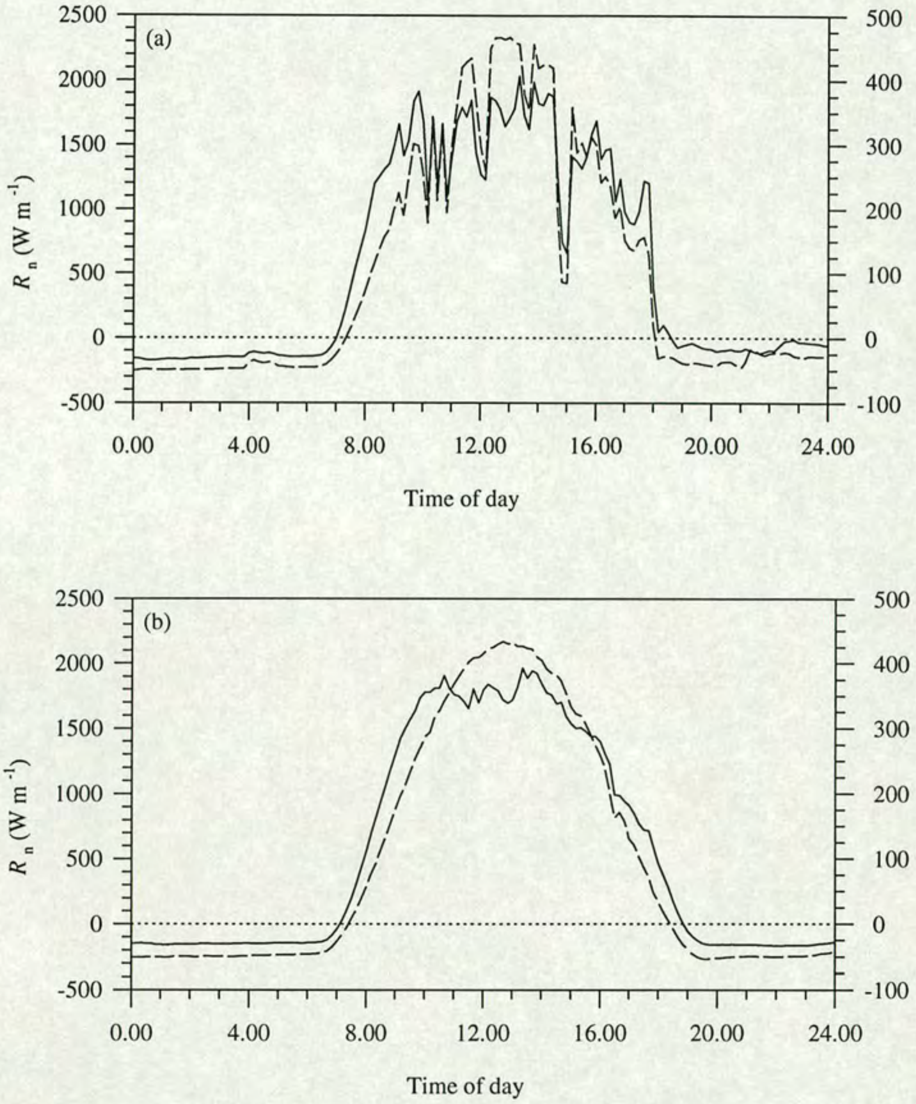


**Figure 5.3:** Net radiation absorbed per unit length of an *Azadirachta indica* windbreak ($R_n$) (———) and net radiation over an adjacent pearl millet (*Pennisetum glaucum*) crop ($R_{nc}$) (– – –) on (a) DOY 197, 1993 and (b) DOY 199, 1993.

The data in Fig. 5.3b were measured on DOY 199, 1993, when skies were clear for most of the day, so that $R_{nc}$ followed a relatively smooth curve over the course of the day. The curve for $R_n$ is not as smooth, probably because of gaps in the canopy which caused variations in absorption of radiation from the sun's direct beam, and has steeper sides and a flatter top than the curve for $R_{nc}$. The north-south orientation and open sides of the windbreak meant that radiation absorption by the windbreak canopy was high even at low solar elevations, so that $R_n$ increased more quickly after sunrise than $R_{nc}$ and then remained relatively constant as the sun traversed the sky overhead. Similar patterns were noted by

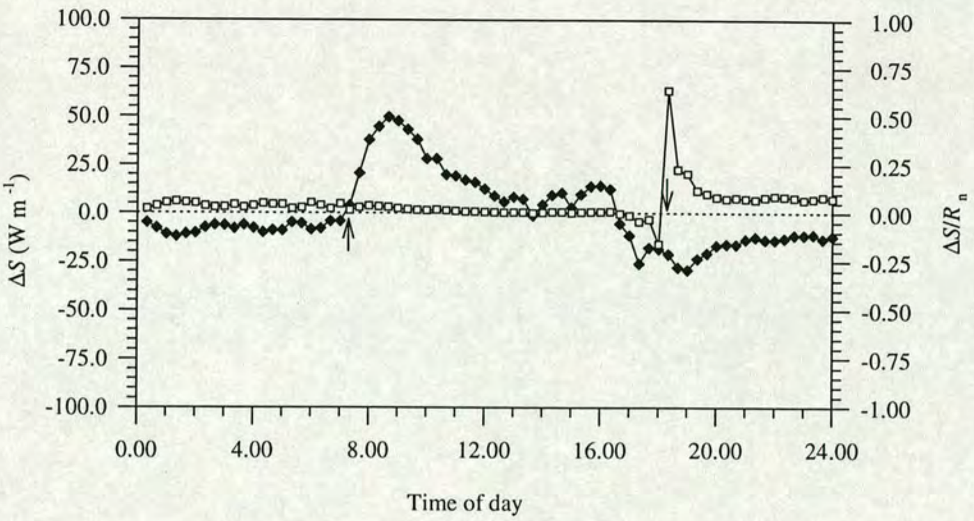


**Figure 5.4:** Heat storage ($\Delta S$) per unit length of an *Azadirachta indica* windbreak (◆) and the fraction of net radiation ($R_n$) absorbed by the windbreak canopy dissipated as $\Delta S$ (ie., $\Delta S/R_n$) (□) for DOY 291, 1992. The arrows indicate the time of transition between positive and negative $R_n$ at sunrise and sunset.

Landsberg *et al.* (1975) for a hedgerow and by McNaughton *et al.* (1992) and Green (1993) for isolated trees. Thus, windbreaks conform to expectations from theory describing the flux of solar radiation to vertical surfaces (van der Hage, 1993) and the radiation climate is more constant during the day, therefore, for trees in windbreaks than for crops or forests.

### **5.5.2** *Heat storage*

Measurements of $\Delta S$ for one day in the late dry season, 1992, are shown in Fig. 5.4. Results from other days on which measurements were made were similar. $\Delta S$ reached 50 W m$^{-1}$ soon after sunrise and fell to -35 W m$^{-1}$ soon after sunset, indicating that these were times when heating and cooling of the woody mass in the windbreak was most rapid. For the remainder of the day, $\Delta S$ lay between 20 W m$^{-1}$ and -20 W m$^{-1}$ and so was much less than $R_n$, which was >1500 W m$^{-1}$ for most of the daylight period. Measured $\Delta S$ thus made up only a very small proportion of $R_n$ and, as shown in Fig. 5.4, accounted for more than a few percent of $R_n$ only near sunset, because the value of $R_n$ was then very small. Values of $\Delta S$ measured in this study represent heat storage in the branches and trunks of the windbreak trees, but it can be shown that storage of heat in the foliage or air within the canopy is also small. Consequently, $\Delta S$ was a negligible component of the energy budgets of the windbreak canopies studied here and is not considered further.

**Table 5.1:** Leaf area and linear leaf area density data for trees in double-row *Azadirachta indica* windbreaks that were instrumented for the determination of the energy budgets of windbreak canopies during four seasons of 1992 and 1993. $A_t$ is the total projected leaf area of the instrumented tree; $L_{w,i}$ is the leaf area density of the portion of the instrumented tree enclosed within a net radiometer array; $L_{w,n}$ is the estimated linear leaf area density for the portion of neighbouring trees enclosed by the array; $L_w$ is the linear leaf area density for the windbreak canopy inside the array; and $f_{tw}$ is the scaling factor used to convert latent and sensible heat fluxes per tree to fluxes per unit length of windbreak.

| Year | Measurement Period (DOY) | Season | $A_t$ ($m^2$) | $L_{w.i}$ ($m^2\ m^{-1}$) | $L_{w.n}$ ($m^2\ m^{-1}$) | $L_w$ ($m^2\ m^{-1}$) | $f_{tw}$ ($m^{-1}$) |
|---|---|---|---|---|---|---|---|
| 1992 | 277-293 | Early dry | 35.7 | 21.1 | 7.8 | 28.9 | 0.81 |
| 1993 | 114-126 | Late dry | 12.3 | 7.3 | 2.9 | 10.2 | 0.83 |
| | 193-203 | Mid-rainy | 26.0 | 15.2 | 6.6 | 21.8 | 0.84 |
| | 260-271 | Late rainy | 55.8 | 27.3 | 12.2 | 39.5 | 0.71 |

### **5.5.3** *Scaling of* λE *and* H *to windbreak length*

The values of $f_{tw}$ used in Equations 5.7 and 5.9 to convert latent and sensible heat fluxes per tree to fluxes per unit length of windbreak are shown in Table 5.1. These values relate to the uniformity of leaf area distribution along the windbreak for each tree studied. If leaf area did not vary along the length of the windbreaks, $f_{tw}$ would have a value of 0.66 and could be replaced in Equations 5.7 and 5.9 with a term simply expressing the number of trees per unit of windbreak length. The higher values of $f_{tw}$ in Table 5.1 arise because linear leaf area densities were higher close to the trunks of trees in the windbreaks than in the gaps between adjacent tree trunks. The linear net radiometers used to measure $R_n$ were centred on the trunks of the trees studied and so use of $f_{tw}$ in Equations 5.7 and 5.9 ensures that $\lambda E$ and $H$ are correctly scaled for the proportion of leaf area on each tree that was enclosed within the net radiometer array.

### **5.5.4** *Windbreak energy budgets*

Energy budgets of *A. indica* windbreaks are shown in Figs. 5.5 to 5.8 for one day in each of the four periods in which measurements were made. For each of these days, $R_n$, $\lambda E$ and $H$ were all determined using independent methods. The accuracy of these methods can be gauged from part (b) of Figs. 5.5 to 5.8, which illustrate closure of the energy budgets (ignoring the influence of $\Delta S$, which was shown to be negligible) by comparing the sum of $\lambda E$ and $H$ with $R_n$. Uncertainties may be associated with each of the methods used, but on each of the days for which data are shown, the energy budget was almost closed. Errors were substantial enough to cause a downward bias in $\lambda E$+$H$ during

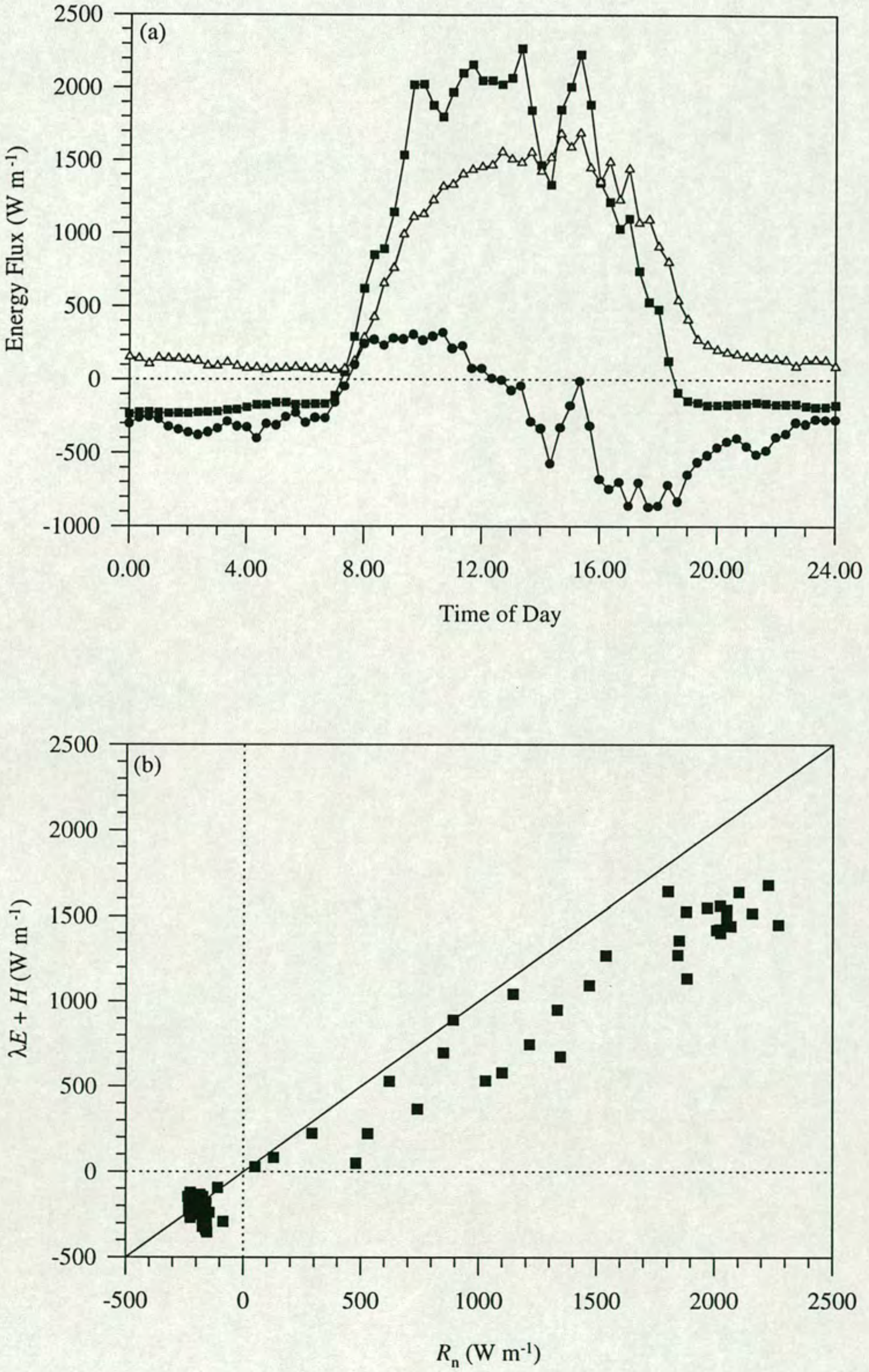


**Figure 5.5:** (a) The energy budget of an *Azadirachta indica* windbreak canopy during the early dry season 1992 (DOY 283). Time courses are shown over the day for net radiation ($R_n$) (■——■), latent heat flux ($\lambda E$) (△——△) and sensible heat flux ($H$) (●——●). (b) Plot of $\lambda E$+$H$ against $R_n$ for DOY 283, 1992. The solid line is 1:1.

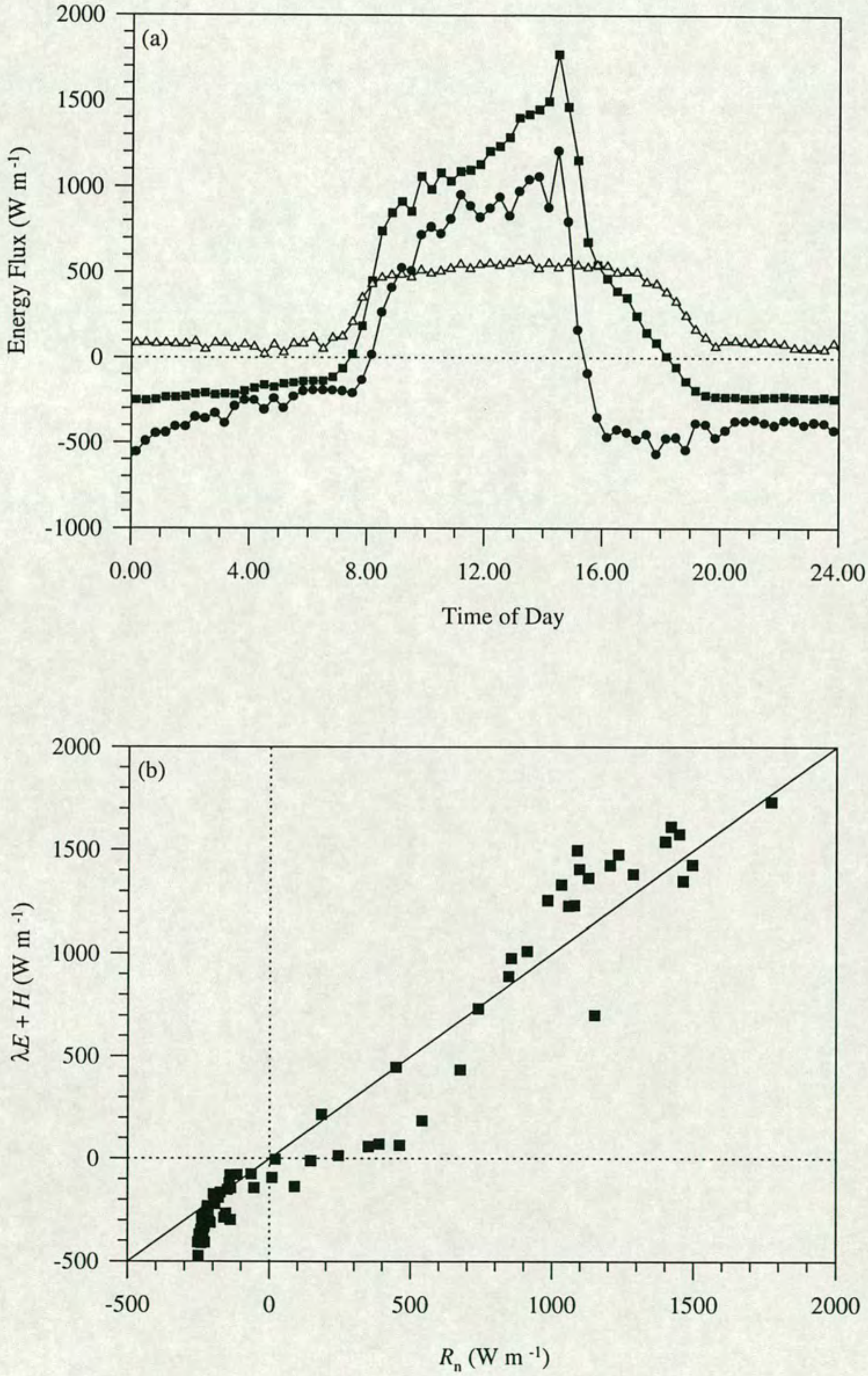


**Figure 5.6:** (a) The energy budget of an *Azadirachta indica* windbreak canopy during the late dry season 1993 (DOY 122). Time courses are shown over the day for net radiation ($R_n$) (■——■), latent heat flux ($\lambda E$) (△——△) and sensible heat flux ($H$) (●——●). (b) Plot of $\lambda E$+$H$ against $R_n$ for DOY 122, 1993. The solid line is 1:1.

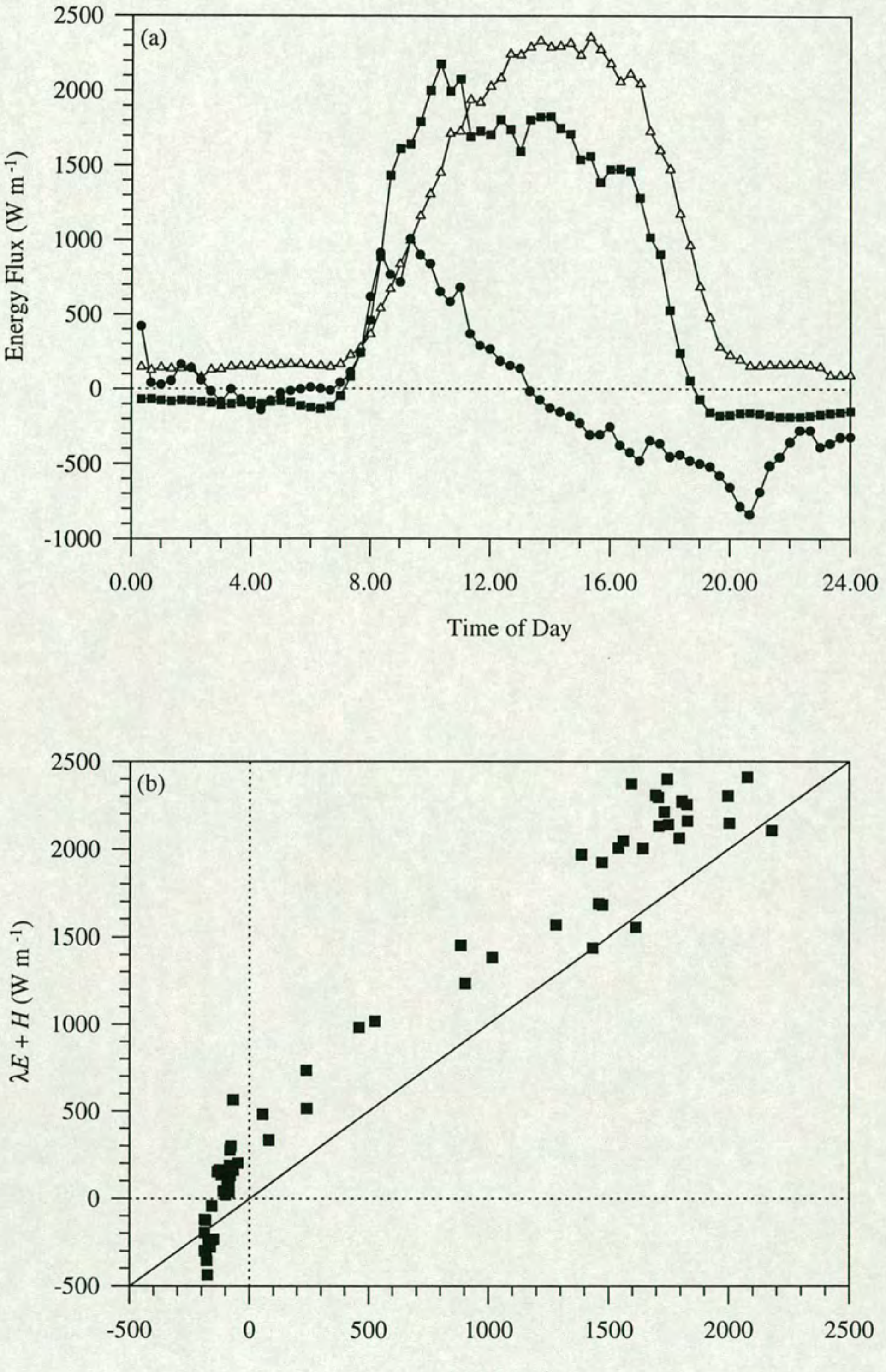


**Figure 5.7:** (a) The energy budget of an *Azadirachta indica* windbreak canopy during the middle of the rainy season 1993 (DOY 198). Time courses are shown over the day for net radiation ($R_n$) (■——■), latent heat flux ($\lambda E$) (△——△) and sensible heat flux ($H$) (●——●). (b) Plot of $\lambda E+H$ against $R_n$ for DOY 198, 1993. The solid line is 1:1.

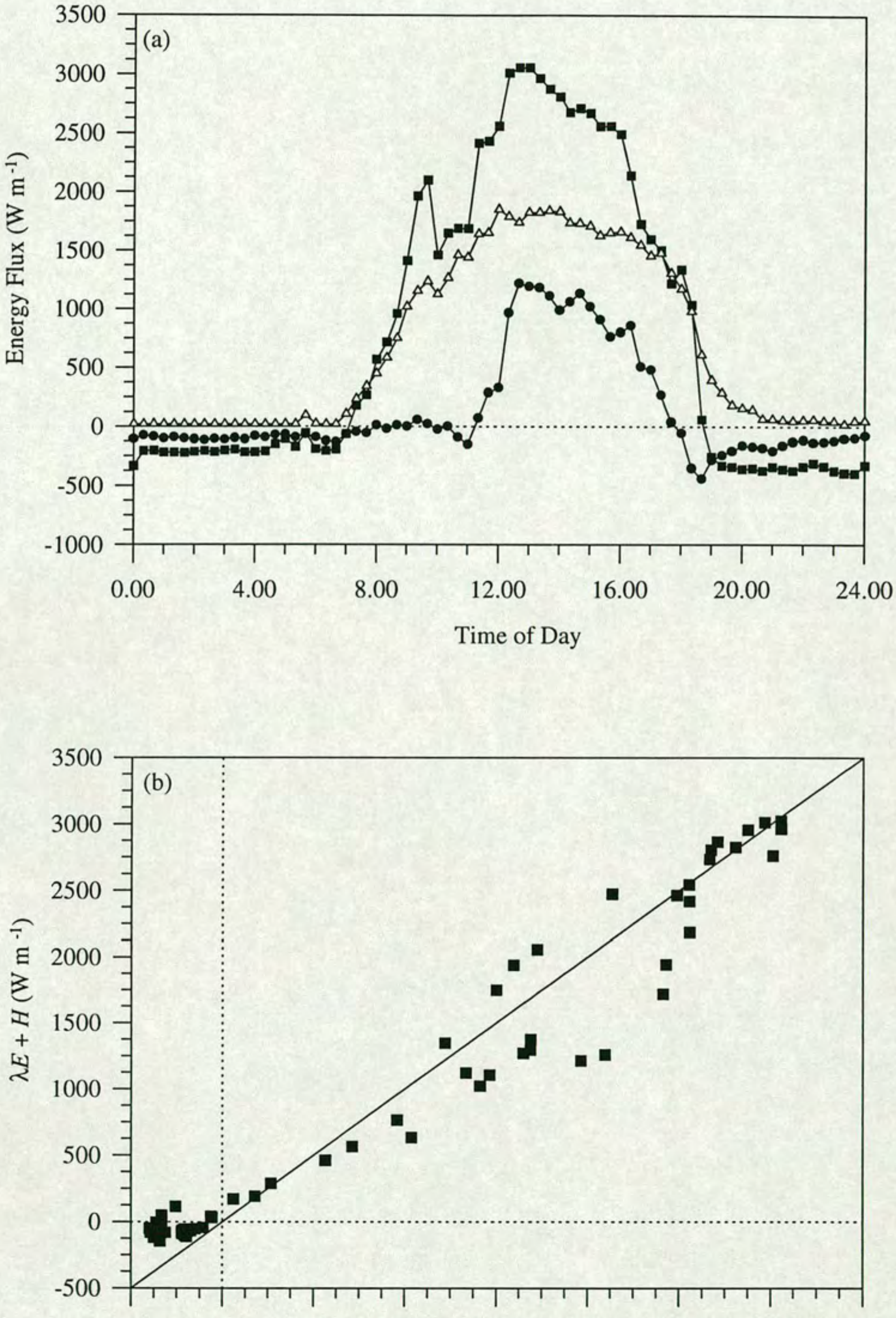


**Figure 5.8:** (a) The energy budget of an *Azadirachta indica* windbreak canopy during the late rainy season 1993 (DOY 264). Time courses are shown over the day for net radiation ($R_n$) (■——■), latent heat flux ($\lambda E$) (△——△) and sensible heat flux ($H$) (●——●). (b) Plot of $\lambda E+H$ against $R_n$ for DOY 264, 1993. The solid line is 1:1.

the early dry season, 1992 (Fig. 5.5b) and to shift $\lambda E+H$ upwards when measurements were made in the middle of the 1993 rainy season (Fig. 5.7b). For the remaining two measurement periods, there was some variability in the relationship between $\lambda E+H$ and $R_n$, but there was general agreement between the two terms (Figs. 5.6b and 5.8b). Errors were not sufficiently large in any period of measurement to hamper interpretation of the ecological significance of the data and were small enough that the techniques used to measure each component of the energy budget can be considered to have worked well.

The methods used to measure $R_n$ and $\lambda E$ have been used effectively by others in different circumstances, but $H$ has not previously been determined from Equation 5.9 on the basis of values of $g_a$ derived from direct measurements of leaf boundary layer conductances and an estimate of $g_{ac}$. Successful closure of the energy budgets for windbreak canopies using values of $H$ measured in this way confirms the accuracy of the methods used to determine $g_a$ that were described in Chapter 4. This suggests that large errors were not caused by the assumption that the relationship defining $g_{ac}$ on the basis of wind speed (Equation 4.15) held for all of the trees studied.

### **5.5.5** *Seasonal variations in windbreak canopy energy budgets*

Total fluxes of each component of the energy budget during daylight hours (defined here as the portion each 24 h when $R_n$ was positive) for the data plotted in Figs. 5.5 to 5.8 are summarised in Table 5.2. Mean values of total fluxes during daylight hours across all of the days on which measurements were made in each period of measurement are given in Table 5.3. From both tables it is evident that $R_n$ varied substantially among the seasons in which measurements were made and comparison of total fluxes of $R_n$ with the linear leaf area densities ($L_w$) of the windbreaks in each season (Table 5.1) indicate that this variation resulted, primarily, from changes over the year in values of $L_w$. Lower $L_w$ meant that less incident radiation was intercepted at the end of the dry season than in the other seasons and $R_n$ was lower as a result. One response of *A. indica* trees to shortages of water during the long dry season is to shed leaves, so that less energy is absorbed and less energy must be dissipated as $\lambda E$ or $H$.

Examination of Tables 5.2 and 5.3 also reveals that total $H$ during daylight hours tended to be small relative to $R_n$ or negative in each season except the late dry season, when a substantial portion of $R_n$ absorbed by the windbreak canopy was dissipated as $H$. During the rainy season and early dry season, $R_n$ was mostly dissipated as $\lambda E$ and, as shown in Tables 5.2 and 5.3, total $\lambda E$ during daylight hours exceeded absorbed $R_n$ in the middle of the rainy season. Consequently, as illustrated in Figs. 5.5 to 5.8, $\lambda E$ was much higher than $H$ for most of the day at all times of year except the late dry season.

**Table 5.2:** Components of the energy budgets of canopies of *Azadirachta indica* windbreaks for one day from each of four seasons of the year. Shown are total fluxes per unit of windbreak length of net radiation ($R_n$), latent heat flux ($\lambda E$), sensible heat flux ($H$) and the exchange flux ($X$) during the daylight period of each day. Bowen ratios ($\beta$) and the ratio $-X/\lambda E$ are also given.

| | | | MJ $m^{-1}$ | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Season | DOY | $R_n$ | $\lambda E$ | $H$ | $X$ | $\beta$ | $-X/\lambda E$ |
| 1992 | Early dry | 283 | 58.8 | 48.1 | -6.2 | -1.3 | -0.12 | 0.03 |
| 1993 | Late dry | 122 | 33.9 | 19.6 | 14.5 | 9.0 | 0.74 | -0.46 |
| | Mid-rainy | 198 | 58.2 | 68.9 | 5.2 | -23.3 | 0.08 | 0.34 |
| | Late rainy | 264 | 79.3 | 61.7 | 16.9 | 4.9 | 0.27 | -0.08 |

Changes over the year in partitioning of $R_n$ into $\lambda E$ and $H$ are reflected in Bowen ratios ($\beta$), where $\beta = H/\lambda E$. Both daily values of $\beta$ shown in Tables 5.2 and 5.3 and changes in $\beta$ during daylight hours, plotted for one day in each season in Fig. 5.9, demonstrate the dominance of $H$ in the late dry season and the dominance of $\lambda E$, indicated by small or negative values of $\beta$, during other times of year. Mean daily maximum values of $D_a$ given in Table 5.3 for each period of measurement establish that the atmosphere was much drier at the end of the dry season than at other times of year and so higher values of $\beta$ at the end of the dry season were not the result of reduced evaporative demand. This

**Table 5.3:** Components of the energy budgets of canopies of *Azadirachta indica* windbreaks measured during four periods of 1992 and 1993. Values of net radiation ($R_n$), latent heat flux ($\lambda E$), sensible heat flux ($H$) and the exchange flux ($X$) are total fluxes during daylight averaged over all $n$ days on which measurements were made in each period. Values of $\lambda E$ and $X$ in brackets were estimated from $\lambda E = R_n - H$ because of frequent failure of the instrumentation used to measure tree transpiration. Also shown are Bowen ratios ($\beta$), $-X/\lambda E$, Priestley and Taylor's factor $\alpha$ and the mean daily maximum vapour pressure deficit ($D_{max}$).

| | Period | | MJ $m^{-1}$ | | | | | | | $D_{max}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | (DOY) | Season | $R_n$ | $\lambda E$ | $H$ | $X$ | $\beta$ | $-X/\lambda E$ | $\alpha$ | (kPa) | $n$ |
| 1992 | 277-293 | Early dry | 58.2 | 49.5 | -11.3 | -2.8 | -0.23 | 0.06 | 1.06 | 4.5 | 10 |
| 1993 | 114-126 | Late dry | 41.8 | 20.2 | 19.5 | 15.2 | 0.97 | -0.75 | 0.57 | 6.5 | 7 |
| | 193-203 | Mid-rainy | 51.5 | [54.2] | -2.7 | [-13.4] | -0.05 | 0.24 | 1.33 | 3.2 | 8 |
| | 260-271 | Late rainy | 95.5 | [87.5] | 8.0 | [-11.1] | 0.09 | 0.13 | 1.15 | 3.4 | 8 |

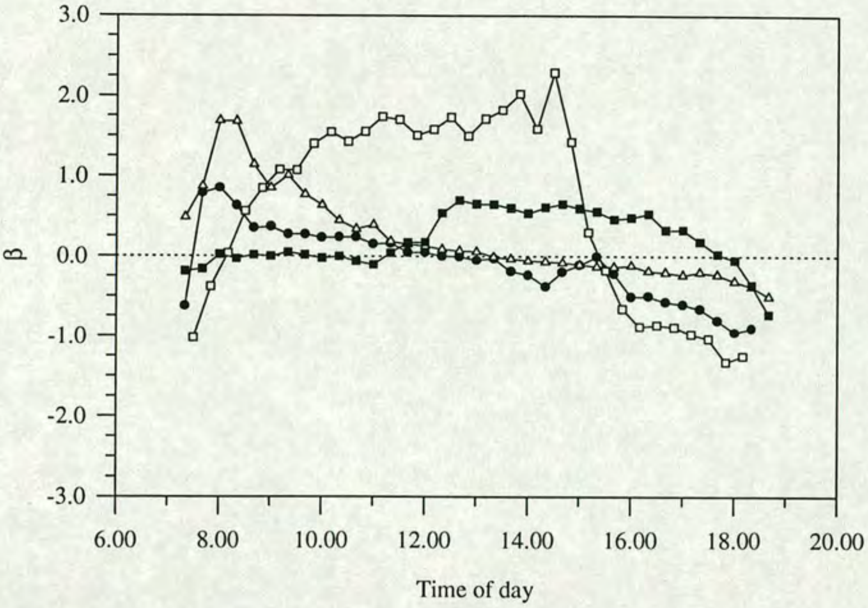


**Figure 5.9:** Time courses of Bowen ratios (β) for canopies of *Azadirachta indica* windbreaks during the daylight periods of: DOY 283, 1992, in the early dry season (●); DOY 122, 1993, in the late dry season (□); DOY 198, 1993, in the middle of the rainy season (△); and DOY 264, 1993, in the late rainy season (■).

suggests that transpiration by the trees in the late dry season was limited by stomatal closure and, after approximately six months without rain at the site, by the availability of moisture in the soil. Partitioning of $R_n$ absorbed by windbreak canopies in the Sahel is thus forced towards $H$ when moisture is in short supply, but during the rainy season and soon afterwards, when plenty of water is usually stored in the soil, transpiration dissipates most or all of the radiation absorbed by the windbreaks.

### **5.5.6** *Exchange fluxes for windbreak canopies*

Negative values of total $X$ during daylight hours were determined on some days in all seasons except the late dry season (Tables 5.2 and 5.3), but were consistently and substantially negative only when measurements were made in the middle of the rainy season. Thus, it appears from values of $-X/\lambda E$ for daylight periods that advection and entrainment drove more than 20% of $\lambda E$ only in the middle of the rainy season. In the late rainy season and early dry season, daily values of $X$ were often close to 0 W m$^{-1}$, so that $\lambda E$ did not appear to deviate greatly from $\lambda E_{eq}$. In the late dry season, daily values of $X$ were strongly positive, indicating depression of $\lambda E$ below $\lambda E_{eq}$. Examination of the values of the Priestley-Taylor coefficient $\alpha$ in Table 5.3 demonstrates the same trends.

**Table 5.4:** Hourly mean values of -*X*/λ*E* for canopies of *Azadirachta indica* windbreaks, where *X* is the exchange flux and λ*E* is the latent heat flux, during one day from the early dry season (DOY 283, 1992), the late dry season (DOY 122, 1993), the middle of the rainy season (DOY 198, 1993) and the late rainy season (DOY 264, 1993). Also shown are mean values of -*X*/λ*E* for the daylight period of each day.

| | -*X*/λ*E* | | | |
|---|---|---|---|---|
| Time of day | DOY 283, 1992 | DOY 122, 1993 | DOY 198, 1993 | DOY 264, 1993 |
| 0800 | -0.28 | 0.76 | 0.39 | 0.31 |
| 0900 | -0.22 | -0.17 | -0.42 | 0.03 |
| 1000 | -0.33 | -0.56 | -0.19 | -0.18 |
| 1100 | -0.15 | -0.69 | 0.01 | 0.08 |
| 1200 | -0.17 | -0.73 | 0.32 | -0.11 |
| 1300 | -0.09 | -0.93 | 0.38 | -0.33 |
| 1400 | -0.01 | -1.23 | 0.37 | -0.24 |
| 1500 | 0.12 | -1.52 | 0.41 | -0.22 |
| 1600 | 0.02 | -0.27 | 0.48 | -0.22 |
| 1700 | 0.35 | 0.34 | 0.45 | 0.06 |
| 1800 | 0.55 | 0.71 | 0.60 | 0.20 |
| mean | 0.03 | -0.46 | 0.34 | -0.08 |

When changes in -*X*/λ*E* over the course of a day are examined, however, substantial effects of advection and entrainment are seen at all times of year. Table 5.4 lists hourly mean values of -*X*/λ*E* for one day from each measurement period. λ*E* was substantially depressed by advection and entrainment for most of the day in the late dry season for which data are shown and, in contrast, between 30 and 60% of λ*E* resulted from advection and entrainment for much of the day from the middle of the rainy season. For the days from the early dry season and late rainy season, Table 5.4 shows that the effects of advection and entrainment were substantial for most of each day, but resulted in both enhancement and depression of λ*E* relative to $\lambda E_{eq}$. Thus, the data in Table 5.4 show that it would be wrong to conclude that advection and entrainment did not influence λ*E* for the windbreaks in the early dry and late rainy seasons, even though daily values of -*X*/λ*E* were near 0. Advection and entrainment affect windbreak canopies in the Sahel at all times of year, but can result in both enhancement and depression of λ*E* relative to $\lambda E_{eq}$.

### 5.5.7 *Influence of canopy conductances on exchange fluxes*

When advection and entrainment are important, their influence on partitioning of $R_n$ into $\lambda E$ and $H$ is controlled by the magnitude of surface conductances for the canopy. This is because the value of $D_a$ relative to $D_{eq}$ determines whether $\lambda E$ is enhanced or depressed by advection and entrainment (McNaughton, 1976b; McNaughton and Jarvis, 1983) and, from Equation 5.2, the value of $D_{eq}$ depends on the surface conductance of the canopy. In order to evaluate the influence of surface conductances on the sign of $X$, surface conductances for the windbreaks ($g_{cw}$), expressed as conductances per unit length of windbreak, were estimated from

$$g_V = \left(\frac{\lambda\gamma}{\rho_a c_p}\right)\frac{E_t}{(e^*(T_s) - e_a)} \tag{5.14a}$$

and

$$g_{cw} = \left(\frac{1}{g_V} - \frac{2}{1.08 g_{bt}} - \frac{1}{g_{ac}}\right)^{-1} f_{tw} \ , \tag{5.14b}$$

where $e^*(T_s)$ is the saturation vapour pressure at $T_s$, $e_a$ is ambient vapour pressure and $g_V$ is the conductance for vapour transfer from the instrumented tree. The factor 2 on the right side of Equation 5.14b appears because *A. indica* is hypostomatous, so that vapour transfer occurs through the boundary layer on one side of a leaf only. The factor 1.08 appears because $g_{bt}$ was determined for heat transfer and conductances for vapour transfer across boundary layers are 1.08 times higher than conductances for heat transfer (Monteith and Unsworth, 1990; Schuepp, 1993). Values of $D_{eq}$ were then calculated using Equation 5.2 with $g_{cw}$ in place of $g_c$ and $R_n$ in place of $A$.

Values of $X$ are plotted against values of $D_{eq}$-$D_a$ for the daylight period of one day from each measurement period in Fig. 5.10. High $g_{cw}$ in the middle of the rainy season resulted in low $D_{eq}$, so that $D_{eq}$ was exceeded by $D_a$ (negative $D_{eq}$-$D_a$) and $\lambda E$ enhanced above $\lambda E_{eq}$ (negative $X$) by advection and entrainment for most of the day. In contrast, low $g_{cw}$ in the late dry season meant that $D_{eq}$ was higher than $D_a$ (positive $D_{eq}$-$D_a$) for most of the day, so that $\lambda E$ was depressed by advection and entrainment (positive $X$) because turbulent motions in the atmosphere then tended to bring air to the surface which restricted transpiration to a rate below the equilibrium rate. In the early dry season and late dry season, $D_a$ exceeded $D_{eq}$ during only part of the day, so that advection and entrainment resulted in enhancement of $\lambda E$ at times and depression of $\lambda E$ at other times.

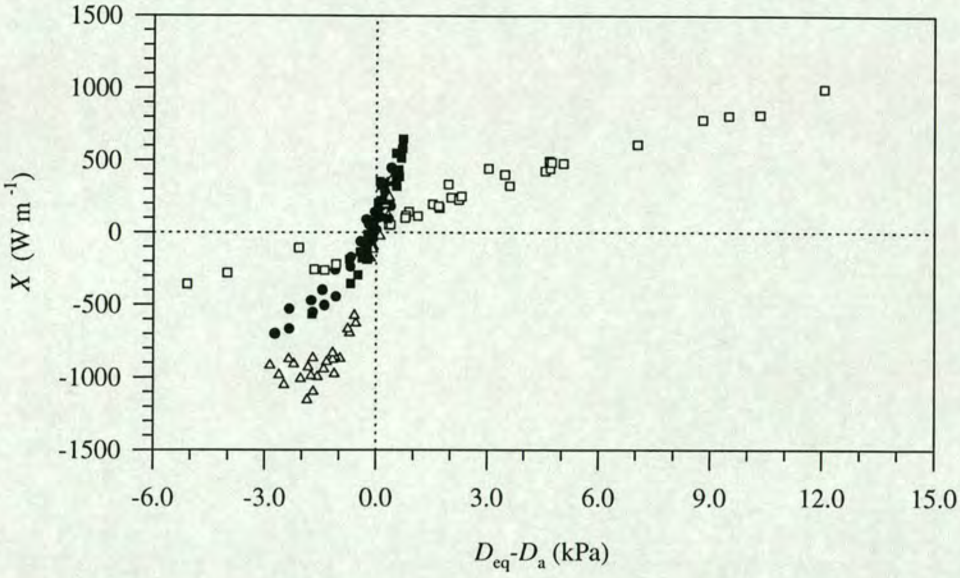


**Figure 5.10:** Dependence of the exchange flux ($X$), where $X=\lambda E_{eq}-\lambda E$, for canopies of *Azadirachta indica* windbreaks on $D_{eq}$-$D_a$, where $D_a$ is the ambient vapour pressure deficit and $D_{eq}$ is the equilibrium vapour pressure deficit for the windbreak canopy, calculated from the canopy conductance for the windbreak using Equation 5.2. Data are from the daylight periods of: DOY 283, 1992, in the early dry season (●); DOY 122, 1993, in the late dry season (□); DOY 198, 1993, in the middle of the rainy season (△); and DOY 264, 1993, in the late rainy season (■).

Energy budgets for canopies of windbreaks are thus strongly affected by advection and entrainment. They are openly exposed to turbulent motions in the atmosphere because they rise above surrounding surfaces, so that eddies rolling across adjacent crops or bare ground can easily penetrate windbreak canopies. Air at the surface of the foliage in windbreaks is, consequently, very unlikely to be resident for a period long enough for it to equilibrate with the fluxes of heat and vapour from the foliage. The eddies moving into windbreak canopies carry air with non-equilibrium $D_a$ because of upwind surface conditions or vertical entrainment at the top of the planetary boundary layer and so partitioning of $R_n$ absorbed by windbreaks into $\lambda E$ and $H$ is shifted away from equilibrium by the exchange of sensible and latent heat at the surface. The magnitude and direction of this exchange is dependent on the surface conductance of the windbreak canopy, so that when trees in windbreaks are stressed because of lack of moisture, energy is exchanged in favour of sensible heat and $\lambda E$ is depressed below the equilibrium rate. When water is plentiful and the trees are densely foliated, surface conductances for the trees are high and transpiration from the windbreaks is enhanced by exchange of sensible heat for latent heat. Thus, windbreaks appear to be able to exert considerable physiological control over the effects of advection and entrainment. When water is abundant, advection and entrainment enhance transpiration from the trees, but when water is scarce, the trees can lower stomatal conductances and shed leaves, so that partitioning of $R_n$ is shifted away from $\lambda E$.

## 5.6 Conclusions

Radiant energy absorbed by windbreak canopies in the Sahel is predominantly dissipated as latent heat when ambient conditions are relatively humid, but when conditions become dry, as occurs in the dry season or during droughts, water use by the trees is reduced and energy is dissipated mostly as sensible heat. Thus, Bowen ratios, $\beta$, for windbreak canopies reached values >1.0 during the middle of the day only when measurements were made in the late dry season and were generally close to 0.0 during wetter periods of the year. However, at all times of year, partitioning of energy by windbreak canopies was strongly affected by exchanges of energy between sensible and latent heat at leaf surfaces resulting from advection and vertical entrainment.

Advection and entrainment thus exert considerable influence on water use by trees in windbreaks in the Sahel. During moist periods of the year, exchange of sensible heat for latent heat at the surface of the windbreaks as a result of advection and entrainment was responsible for up to 60% of $\lambda E$, thus enhancing $\lambda E$ above $\lambda E_{eq}$. At very dry times of the year, conversely, advection and entrainment resulted in depression of $\lambda E$ below $\lambda E_{eq}$, so that $\lambda E$ was as little as 40% of $\lambda E_{eq}$. Depression of $\lambda E$ by advection and entrainment occurred because surface conductances of the windbreaks were reduced in the late dry season in response to the dry environment, so that $D_{eq}$ was usually higher than $D_a$. Atmospheric motions in the late dry season thus supplied air to the surfaces of leaves in the windbreaks with a lower evaporative demand than air at the surface would have had if equilibration of air at the surface with the fluxes of heat and vapour from the foliage of the windbreak trees had been possible. In contrast, during more humid periods, $D_{eq}$ was often less than $D_a$ because surface conductances were higher, so that atmospheric motions continually delivered air to the surface of the windbreaks with a higher evaporative demand than would have occurred at equilibrium.

McNaughton (1983) demonstrated that windbreaks protect crops in their lee from enhancement of evapotranspiration by advection and entrainment, so that (all else being equal) water use by crops should be lower behind windbreaks than in unsheltered fields when $D_a$ for the bulk atmosphere is higher than $D_{eq}$ at the surface of the crop (McNaughton, 1988). Miller *et al.* (1973) found that crop evapotranspiration was reduced by an average of 20% when measured behind a fence windbreak, but their experimental design ensured that effects of shelter on growth and water use by the crop were not confounded. Crops growing behind windbreaks are often larger and leafier than unsheltered crops (Davis and Norman, 1988), so that the reduction in enhancement of evapotranspiration by advection and entrainment offered by shelter is often offset by the effect of increased leaf area on water use by the crop. Hence, Ogbuehi and Brandle (1981) found that crop water use was not influenced by shelter and Brenner (1991) found that transpiration of a millet crop in the Sahel increased behind a windbreak because the influence of higher surface conductances and temperatures on transpiration was larger than the effect of reduced turbulent transport from the sheltered crop. Whether evapotranspiration from windbreak-sheltered crops is increased or decreased, it is important that water use by the trees which form the windbreak is not neglected when water budgets for windbreak-crop associations and unsheltered fields are compared. During the cropping season in the Sahel, the soil is usually moist and evaporative demand by the atmosphere is usually relatively low during years of normal rainfall, so that any reduction in crop transpiration in shelter will be offset by enhancement of tree transpiration by advection and entrainment and any increase in crop transpiration behind windbreaks will be augmented by enhanced water use by the trees.

Further study is required to quantify the effects of tree transpiration on the water budgets of windbreak systems in the Sahel, but the results reported here and the results presented by Brenner (1991) demonstrate that windbreak systems should not be expected to conserve soil moisture in the Sahel. Windbreaks are excellent tools for controlling degradation of deforested semi-arid lands (Ritchie, 1988) and shelter may increase the water use efficiency of crops (Davis and Norman, 1988; Brenner, 1991), but windbreaks do not conserve water in the Sahel. Thus windbreaks are unlikely to have beneficial effects on crop yields in the northern reaches of the Sahel where crop growth is limited by moisture availability in all but the wettest years. To the south, however, where annual rainfall is higher and crop growth is less often limited by moisture availability (Payne *et al.*, 1990; Zaongo *et al.*, 1994), increased water use by trees and crops where windbreaks are established may increase the productivity of land in years when drought does not occur.

The effects of advection and entrainment on transpiration by windbreak trees are important determinants of the severity of competition between trees and crops for water. When water use by trees is substantially enhanced as a result of advection and entrainment while adjacent crops are stressed by lack of moisture, competition between trees and crops for moisture will be severe and will exacerbate stress in the crops. Under conditions where advection and entrainment depress transpiration by the windbreaks, whether for portions of the day or, under very dry conditions, for the entire day, competition will be less severe. Thus, if efforts are made to construct models of competitive interactions in windbreak-crop associations or other agroforestry systems used in the semi-arid tropics, it is imperative that the influence of advection and entrainment on tree transpiration is adequately modelled. Whether advection and entrainment enhance or depress transpiration by windbreak trees depends on the magnitude of the surface conductance of the trees through its influence on $D_{eq}$. Before competition between trees and crops can be modelled, therefore, a full understanding is required of the responses of the stomata of windbreak foliage to environmental conditions and of the effects of changes in surface conductances of windbreak canopies on transpiration by the trees.

# Chapter 6

# Physiological Control of Transpiration by Windbreak Canopies in the Sahel

## 6.1 Introduction

Physiological control is exerted over transpiration when changes in stomatal conductance result in changes in the flux of water vapour from the surface of vegetation. Transfer of vapour from vegetation to the atmosphere begins with the diffusion of vapour through stomatal pores, along gradients in humidity between the interior of leaves and the air in contact with leaf surfaces. Changes in stomatal aperture perfectly regulate the flux of vapour through individual pores (Jarvis and McNaughton, 1986), but may not influence transpiration from a whole plant or canopy if air adjacent to the leaves is isolated aerodynamically from surrounding air by thick boundary layers.

Where boundary layers prevent ambient air impinging on the surface of plants, the plant or canopy is said to be decoupled from ambient air and the vapour pressure deficit of air at the surface ($D_s$) approaches a local equilibrium, $D_{eq}$. Changes in canopy conductances resulting from opening or closing of stomata affect $D_{eq}$, but the consequent change in the gradient in vapour pressure across the stomatal pores counteracts the effects of stomatal action, so that changes in canopy conductance for aerodynamically decoupled vegetation have little influence on transpiration (Jarvis and McNaughton, 1986; Collatz *et al.*, 1991).

In contrast, when vegetation is not sheltered from turbulent motions in the atmosphere, the canopy is said to be well coupled to the air overhead because air at the surface is continually replaced by ambient air and the ambient vapour pressure deficit ($D_a$) is imposed at the surface of leaves in the canopy. For well-coupled canopies, therefore, the gradient in vapour pressure across stomatal pores is not dependent on equilibration of air and vapour fluxes at the surface. Thus, changes in stomatal and canopy conductance effectively regulate water loss from well-coupled leaves and canopies because there is little feedback between transpiration and $D_s$ (Jarvis and McNaughton, 1986; Collatz *et al.*, 1991; McNaughton and Jarvis, 1991).

Crops sheltered by windbreaks are decoupled from the ambient airstream because turbulent transport is suppressed in a boundary layer overlying the sheltered zone in the lee of windbreaks (McNaughton, 1983). This reduces the influence of advection and vertical entrainment on evapotranspiration from the crop, so that evapotranspiration from a sheltered crop has been observed to approach an equilibrium rate determined chiefly by net radiation absorption by the crop (Judd and McAneney, 1984; McAneney *et al.*, 1992). Decoupling of sheltered crops also reduces physiological control of transpiration relative to unsheltered crops because the reduction in aerodynamic conductance over a sheltered crop causes $D_s$ for the crop to tend towards $D_{eq}$ (McNaughton, 1988).

Immediately adjacent to sheltered crops, trees in windbreaks are aerodynamically rough and so should, in contrast to the crop, be closely coupled to ambient air. Advective effects on transpiration from windbreaks are consequently strong, as demonstrated in Chapter 5, because atmospheric turbulence tends to impose $D_a$ at the evaporating surface of the trees. Feedbacks between $D_s$ and transpiration by the trees should, therefore, be non-existent or weak, so that trees in windbreaks should be able to control transpiration closely through physiologically-mediated adjustments in stomatal conductances. The extent to which this is true depends on a balance between the tendency of vapour fluxes from stomatal pores to humidify air at leaf surfaces and the tendency of ambient air to impinge on the leaf surfaces and prevent this from occurring. Aerodynamic conductances control the penetration of ambient air into the windbreak canopy and surface conductances regulate fluxes of vapour into the air adjacent to the surfaces of leaves in the canopy. The extent of physiological control of transpiration from trees in windbreaks was assessed, consequently, by examining the relative magnitudes of the aerodynamic and surface conductances of windbreaks of *Azadirachta indica* A. Juss. trees. The windbreaks studied were growing in the Sahelian zone of West Africa, an environment where atmospheric demand for water can be very high while the availability of water for plant growth can be severely limited during dry periods, so that knowledge of the environmental and physiological variables controlling water use by component plants of windbreak systems in the Sahel should help efforts to devise management strategies for coping with competition for water between trees and crops and aid in the development of models of water use in agroforestry in the region.

## 6.2 Theory

### **6.2.1** *Determination of windbreak transpiration*

Transpiration per unit of windbreak length ($E$) can be estimated from measurements of transpiration by a single tree growing in windbreak ($E_t$) using

$$E = E_t f_{tw} , \tag{6.1}$$

where $f_{tw}$ is a scaling factor that converts $E_t$ to $E$ on the basis of leaf area. The factor $f_{tw}$ is given by

$$f_{tw} = \frac{L_w}{A_t}, \tag{6.2}$$

where $L_w$ is the linear projected leaf area density of the windbreak (ie. projected leaf area per unit length of windbreak) and $A_t$ is the projected leaf area of the tree on which $E_t$ is measured.

### **6.2.2** *Determination of the aerodynamic conductance of a windbreak*

The aerodynamic conductance for heat transfer ($g_a$) of a single tree growing in a windbreak can be found from

$$\frac{1}{g_a} = \frac{1}{g_{bt}} + \frac{1}{g_{ac}}. \tag{6.3}$$

Here, $g_{bt}$ is the summed leaf boundary layer conductance for the crown of the tree, calculated as the parallel sum of the boundary layer conductances for all leaves in the tree crown, and $g_{ac}$ is the conductance for transfer between the outer limits of the leaf boundary layers and a reference level outside the tree crown. The aerodynamic conductance for heat transfer for the windbreak ($g_{aw}$), on the basis of windbreak length, is then

$$g_{aw} = g_a f_{tw} . \tag{6.4}$$

**6.2.3** *Estimation of the surface conductance of a windbreak*

The conductance for vapour transfer from a single tree in a windbreak ($g_V$) can be calculated from

$$g_V = \left(\frac{\lambda\gamma}{\rho_a c_p}\right)\frac{E_t}{(e^*(T_s) - e_a)}, \tag{6.5}$$

where $\lambda$ is the latent heat of vaporisation, $\gamma$ is the psychrometric constant, $\rho_a$ is the density of air, $c_p$ is the specific heat capacity of air at constant pressure, $e^*(T_s)$ is the saturation vapour pressure at the surface temperature of the windbreak canopy ($T_s$) and $e_a$ is ambient vapour pressure. The surface conductance of a windbreak ($g_{cw}$), per unit of windbreak length, is then given by

$$g_{cw} = \left(\frac{1}{g_V} - \frac{2}{1.08 g_{bt}} - \frac{1}{g_{ac}}\right)^{-1} f_{tw}\,. \tag{6.6}$$

The factor 2 in the $g_{bt}$ term of Equation 6.6 appears where the species of tree under study, like *A. indica*, is hypostomatous, so that vapour transfer occurs only through the boundary layer on one side of a leaf. The factor 1.08 accounts for the difference in the molecular diffusivities of heat and water vapour in boundary layers (Monteith and Unsworth, 1990) and is included because $g_{bt}$, as defined here, is a conductance for the transfer of heat, whereas $g_{cw}$ is a conductance for vapour transfer.

**6.2.4** *Coupling of windbreak canopies to the atmosphere*

When aerodynamic conductances between the surface of vegetation and the atmosphere are high, air at transpiring surfaces is strongly coupled to ambient air and $D_a$ drives transpiration at leaf surfaces. This can be verified by estimating the vapour pressure, $e_{cs}$, of air in contact with the surfaces of leaves in the canopy. If air within the stomatal cavities of leaves is assumed to be saturated at $T_s$ , values of $e_{cs}$ for windbreaks can be estimated using

$$e_{cs} = e^*(T_s) - \left(\frac{\lambda\gamma}{\rho_a c_p}\right)\frac{E}{g_{cw}}. \tag{6.7}$$

When $D_a$ is imposed at the surface, the transpiration rate tends towards a limit termed the imposed transpiration rate ($E_{imp}$) (Jarvis and McNaughton, 1986), which, per unit length of windbreak, is found from

$$E_{\mathrm{imp}} = \frac{\rho_{\mathrm{a}} c_p}{\lambda\gamma} g_{\mathrm{cw}} D_{\mathrm{a}} . \qquad (6.8)$$

When aerodynamic conductances above vegetation are low, the surface is decoupled from the overlying atmosphere and equilibration of air adjacent to the vegetation with fluxes of heat and vapour causes $D_s$ to approach $D_{eq}$ (McNaughton and Jarvis, 1983; Jarvis and McNaughton, 1986). For a windbreak canopy in which heat storage is negligible, $D_{eq}$ is given by

$$D_{\mathrm{eq}} = \left( \frac{s}{s+\gamma} \right) \frac{\gamma R_{\mathrm{n}}}{\rho_{\mathrm{a}} c_p g_{\mathrm{cw}}} , \qquad (6.9)$$

where $s$ is the slope of the saturation vapour pressure curve at the surface temperature and $R_n$ is net radiation absorbed per unit length of windbreak. With $D_s$=$D_{eq}$, $E$ is driven at an equilibrium rate, $E_{eq}$, which is found from

$$E_{\mathrm{eq}} = \left( \frac{s}{s+\gamma} \right) \frac{R_{\mathrm{n}}}{\lambda} . \qquad (6.10)$$

When vegetation is decoupled from ambient air, therefore, $E$ depends on net radiation and, to a lesser extent, temperature, since $s$ is a function of temperature.

At intermediate levels of coupling between vegetation and the atmosphere, $E$ varies between the two limits defined by Equations 6.8 and 6.10 according to a form of the Penman-Monteith equation derived by Jarvis and McNaughton (1986) as

$$E = \Omega E_{\mathrm{eq}} + (1-\Omega) E_{\mathrm{imp}} . \qquad (6.11)$$

Here, $\Omega$ is a dimensionless "decoupling coefficient" with a range of 0 to 1 which quantifies coupling between vegetative canopies and ambient air. For a windbreak for which $\Omega$=1.0, consequently, the surface of the canopy is completely decoupled from overhead conditions, so that $E$ is chiefly determined by $R_n$ (Equation 6.10) and changes in $g_{cw}$ have no effect on $E$. Stomata of leaves in the canopy of a fully-decoupled windbreak thus do not control water loss from the canopy and physiological responses of stomata to the environment do not regulate transpiration. In contrast, at the limit $\Omega$=0.0, a windbreak is completely coupled to the atmosphere and $E$ depends on $D_a$ and $g_{cw}$ (Equation 6.8), so that a fractional change in $g_{cw}$ causes an equal fractional change in transpiration and stomata have complete control over transpiration. At intermediate levels of $\Omega$, fractional changes in $g_{cw}$ cause decreasing fractional changes in $E$ as $\Omega$ approaches 1 and physiological control over transpiration diminishes (Jarvis and McNaughton, 1986).

Coupling of vegetation to the atmosphere, and therefore physiological control of transpiration, thus depends on the balance between the imposition of $D_a$ at the surface and the tendency of the surface to equilibrate with overlying air (Meinzer and Grantz, 1989). Coupling is consequently a function of the ratio of the aerodynamic and surface conductances for a canopy (Jarvis and McNaughton, 1986). If the effects of changes in surface temperature on net radiation are assumed to have only a minor influence on $\Omega$ (McNaughton and Jarvis, 1991), values of $\Omega$ appropriate to windbreaks of hypostomatous trees are given by (Jarvis and McNaughton, 1986)

$$\Omega = \frac{\varepsilon + 2}{\varepsilon + 2 + g_{aw} / g_{cw}}, \tag{6.12}$$

where $\varepsilon = s/\gamma$ and the value 2 in the numerator and denominator is the ratio of the aerodynamic conductances for heat and vapour transfer for hypostomatous leaves. Coupling is strong when $g_{aw}$ is high because $D_s$ then tends towards $D_a$, but diminishes when $g_{cw}$ is high because $D_s$ then tends to deviate from $D_a$ (Jarvis and McNaughton, 1986; Meinzer and Grantz, 1989).

### 6.3 Materials and methods

The windbreaks studied were formed by double rows of alternately planted *A. indica* trees, with 1.5 m between rows and 3 m between trees in the same row. The windbreaks ran north-south, were 50 m long with 30 m of cropland between parallel windbreaks and they were managed as hedge windbreaks and so were pruned to 2 m from a height of 4 to 5 m at the end of every dry season. During the rainy season, pearl millet (*Pennisetum glaucum* (L.) R. Br.) was grown between the windbreaks.

The windbreaks were located at Sadoré (13°14'N, 2°16'E), Niger, on the research farm of the ICRISAT Sahelian Centre, about 45 km south of the city of Niamey. The region has a Sahelian climate, with 545 mm of rain falling annually on average at Niamey during a single, short rainy season between June and September. The remainder of the year is dry and hot, with monthly means for daily maximum temperatures ranging from 33 to 40 °C (Sivakumar *et al.*, 1993).

Measurements required for the analysis of coupling between windbreaks and the atmosphere were made during four periods in 1992 and 1993. These were: (1) DOY 277-293, 1992, in the early dry season; (2) DOY 114-126, 1993, in the late dry season; (3) DOY 193-203, 1993, in the middle of the rainy season; and (4) DOY 260-271, 1993, in the late rainy season. During each period, measurements were made on a single tree in one windbreak, hereafter called the instrumented tree, and the data were then converted to values per unit of windbreak length using the scaling factor, $f_{\mathrm{tw}}$. A different tree was used in each period.

### **6.3.1** *Reference measurements*

An aspirated psychrometer (Allen *et al.*, 1994) and a cup anemometer (A100R, Vector Instruments Ltd., Rhyl, UK.), mounted at a height of 4 m on a mast directly adjacent to the instrumented tree in each period of observation, were used to measure reference values of ambient air temperature ($T_{\mathrm{a}}$), $D_{\mathrm{a}}$ and wind speed ($u$). Values of $R_{\mathrm{n}}$ were measured using an array of eight linear net radiometers (Swissteco, Melbourne, Australia), 0.88 m in length, deployed in a regular octagon enclosing a section of windbreak centred on the trunk of the instrumented tree using the method developed by Thorpe (1978) and described in Chapter 5. Reference data were logged at 30 s intervals and averaged over periods of 20 min using a 21X data logger (Campbell Scientific Ltd., Shepshed, UK.).

### **6.3.2** *Estimation of* $\mathrm{f}_{tw}$

In order to calculate $f_{\mathrm{tw}}$ using Equation 6.2, values of $L_{\mathrm{w}}$ and $A_{\mathrm{t}}$ were measured at the conclusion of each period of measurement. The crown of the instrumented tree was divided into sections by splitting the crown horizontally and vertically into thirds, using flagging tape to demarcate boundaries between sections. All leaves were then harvested and the projected leaf area for each section estimated as the product of the total dry mass and specific leaf area of leaves in each section. Specific leaf areas were determined from the projected leaf area, measured using a leaf area meter (LI-3100, Li-Cor Inc., Lincoln NE, USA.), and dry mass of a subsample of leaves harvested from each section. The value of $A_t$ for the tree was then calculated by summing the leaf areas of all sections of the crown. The value of $L_w$ was determined by estimating the projected leaf area contributed to unit length of windbreak by both the instrumented tree and by neigbouring trees in the portion of the windbreak centred on the trunk of the instrumented tree, as described in Chapter 5.

### **6.3.3** *Measurement of transpiration*

In each period of measurement, $E_t$ was determined using the heat-pulse technique to measure sap flow in the trunk of the instrumented tree. Measurements were made using the procedures described by Edwards and Warwick (1984) and so four sets of heat-pulse probes, each comprising a heater and two probes containing thermistors, were used to determine sap velocities at a different depth below the cambium of the tree stem at each of four evenly-spaced positions around the circumference of the stem. Sap velocities at each position were derived from the upward velocity of short (1 s) pulses of heat by accounting for the thermal properties of moist wood according to Marshall (1958) and for thermal inhomogeneities caused by the implantation of the probes into the stem according to Swanson and Whitfield (1981). Sap flux densities were calculated from measured sap velocities and volume flow rates of sap in the trunks of each tree were calculated from the integral over the sapwood cross-section of a second-order least squares regression equation fitted to the sap flux density profile between the cambium and the heartwood of each stem (Edwards and Warwick, 1984; Green and Clothier, 1988) or, where this resulted in extrapolation to unrealistically high values of sap flux, from the integral of a step function of sap flux density with radial depth (Hatton *et al.*, 1990). Thus, $E_t$, expressed as a mass flow rate per tree, was calculated from (Green and Clothier, 1988; Green, 1993)

$$E_t = \rho_w 2\pi \int_h^R r_d q'_v(r_d) \mathrm{d}r_d \,, \qquad (6.13)$$

where $\rho_w$ is the density of water and $q'_v(r_d)$ is volumetric sap flux density as a function of radial depth, $r_d$, in a trunk with a radius at the cambium of $R$ and a radius for the heartwood of $h$.

During all periods of observation, measurements were made and recorded at 20 min intervals using a heat-pulse logger (Custom HP1, Hort Research, Palmerston North, New Zealand). Tests in the laboratory and in the field of the validity of sap flow rates measured in *A. indica* with the heat-pulse technique, using methods outlined by Green and Clothier (1988), showed, however, that measured sap flow must be corrected because of thermal inhomogeneities resulting from the anatomy of *A. indica* wood. Thus, on the basis of comparisons of measured and actual sap flow (Appendix A), all measured sap flow rates ($F_h$) were corrected using

$$F_c = 1.62 F_h \,, \tag{6.14}$$

where $F_c$ is corrected sap flow.

### 6.3.4 *Estimation of aerodynamic conductances*

In each period of measurement, leaf boundary layer conductances ($g_b$) were measured at three positions in each of three horizontal layers of the crown of the instrumented tree using heated leaf-replica pairs. Boundary layer conductances are calculated using this technique from the difference in temperature between heated and unheated replicas in a pair and the power input to the heated replica (Leuning, 1989; Leuning and Foster, 1990; Brenner, 1991). The replicas used in this study were models of *A. indica* leaflets, data were logged using a 21X data logger and AM32 multiplexer (Campbell Scientific Ltd., Shepshed, UK.) and the values of $g_b$ calculated were mean values for 10 min periods, as described in Chapter 4.

Summed leaf boundary layer conductances ($g_{bt}$) for the crown of the instrumented tree were calculated from measured values of $g_b$ by assuming that boundary layer conductances for all individual leaves in a tree crown are conductances in parallel, so that $g_{bt}$ is given by

$$g_{bt} = \sum_{j=1}^{3} \left( \overline{g_{bj}} A_{lj} \right), \tag{6.15}$$

where $\overline{g_{\mathrm{b}j}}$ is the mean value of $g_{\mathrm{b}}$ measured in each layer, $j$, of the tree crown and $A_{\mathrm{l}j}$ is the projected leaf area of each layer. The response of $g_{\mathrm{bt}}$ to $u$ was then modelled for the tree studied in each period of measurement using non-linear regression, so that values of $g_{\mathrm{bt}}$ could be estimated from measured wind speeds at all times of each period of observation and used to calculate values of $g_{\mathrm{a}}$ and $g_{\mathrm{aw}}$ with Equations 6.3 and 6.4.

Values of $g_{\mathrm{ac}}$, also required to calculate $g_{\mathrm{a}}$ and $g_{\mathrm{aw}}$, were estimated using

$$\frac{1}{g_{\mathrm{ac}}} = \left(0.187 + 0.226u^{1.131}\right)^{-1} - \left(0.394 + 1.212u^{0.554}\right)^{-1}. \qquad (6.16)$$

Equation 6.16 was derived from measurements of $g_{\mathrm{bt}}$ and estimates of bulk aerodynamic conductances for artificially-wetted crowns of *A. indica* trees in windbreaks at the site, made using methods described by Teklehaimanot and Jarvis (1991), as shown in Chapter 4. Use of this equation to calculate $g_{\mathrm{ac}}$ implies the assumption that it holds for all of the trees studied.

### **6.3.5** *Measurement of surface temperature*

Estimation of $g_{\mathrm{cw}}$ using Equations 6.5 and 6.6 requires knowledge of $T_{\mathrm{s}}$, the surface temperature of the windbreak canopy. Values of $T_{\mathrm{s}}$ were determined by measuring the temperatures of leaves in the crown of the instrumented tree using copper-constantan thermocouple junctions made from 0.2 mm-diameter teflon-coated wire (TC Ltd., Uxbridge, UK.) and attached to the undersides of five leaves in each of three layers of the crown with porous surgical tape. The thermocouples in each layer were connected in parallel with their reference junctions located at the dry bulb of the psychrometer at reference height, so that mean leaf-air temperature difference $(\overline{T_{\mathrm{l}} - T_{\mathrm{a}}})$ was measured directly for each layer. Values of $(\overline{T_{\mathrm{l}} - T_{\mathrm{a}}})$ were recorded on the 21X data logger with data from the reference height. The crown-air temperature difference ($T_{\mathrm{s}}$-$T_{\mathrm{a}}$) was then estimated by weighting values of $(\overline{T_{\mathrm{l}} - T_{\mathrm{a}}})$ for each layer of the crown by leaf area using

$$(T_{\mathrm{s}} - T_{\mathrm{a}}) = \frac{1}{A_{\mathrm{t}}} \sum_{j=1}^{3} (\overline{T_{\mathrm{l}} - T_{\mathrm{a}}})_j \, A_{\mathrm{l}j}\,. \qquad (6.17)$$

Values of $T_{\mathrm{s}}$ were then found by adding the dry bulb temperature ($T_{\mathrm{a}}$) to ($T_{\mathrm{s}}$-$T_{\mathrm{a}}$).

## 6.4 Results and discussion

### 6.4.1 *Aerodynamic conductances*

Values of $g_{aw}$ for one 24 h period from each period of measurement are shown in Fig. 6.1a. These data were derived from measured $u$ and the projected leaf areas and values of $f_{tw}$ shown in Table 6.1 using Equations 6.3, 6.4, 6.15 and 6.16. Fluctuations in values of $g_{aw}$ occurred within each 24 h period because of variations in $u$ (Fig. 6.1b), but despite large disparities in leaf area among the trees studied in each season, the magnitude of $g_{aw}$ was generally similar in each period of measurement. In the late dry season, for example, $A_t$ was low as a result of leaf loss from the *A. indica* trees over the dry season, but wind speeds were high in comparison to wind speeds at other times of year (Fig. 6.1b), thus compensating values of $g_{aw}$ in the late dry season for the effect of low leaf area. In general, therefore, aerodynamic conductances for the *A. indica* windbreaks studied were largely insensitive to seasonal changes in the canopies of the windbreaks.

### 6.4.2 *Surface conductances*

Values of $g_{cw}$ varied much more strongly among seasons than values of $g_{aw}$ (Fig. 6.2), with $g_{cw}$ highest during the rainy season and decreasing as the environment became drier, so that the lowest values of $g_{cw}$ were found in the late dry season. Variations in the surface conductances for canopies of vegetation may result from changes in leaf area or from stomatal responses to changing environmental conditions (McNaughton and Jarvis, 1983; Kelliher *et al.*, 1995), but much of the seasonal variation in $g_{cw}$ shown in Fig. 6.2 can be attributed to the large changes in the leaf area of the windbreak trees between the rainy season and the late dry season because the drastically lower values of $g_{cw}$ found in the late dry season are associated with a large reduction in $L_w$ (Table 6.1). Changes in stomatal conductances may also have contributed to the variation in $g_{cw}$, however, because daily maximum values of the mean stomatal conductance ( $\overline{g_s^{max}}$ ) for the windbreak canopy (Table 6.2), approximated from daily maximum values of $g_{cw}$ ( $g_{cw}^{max}$ ) using

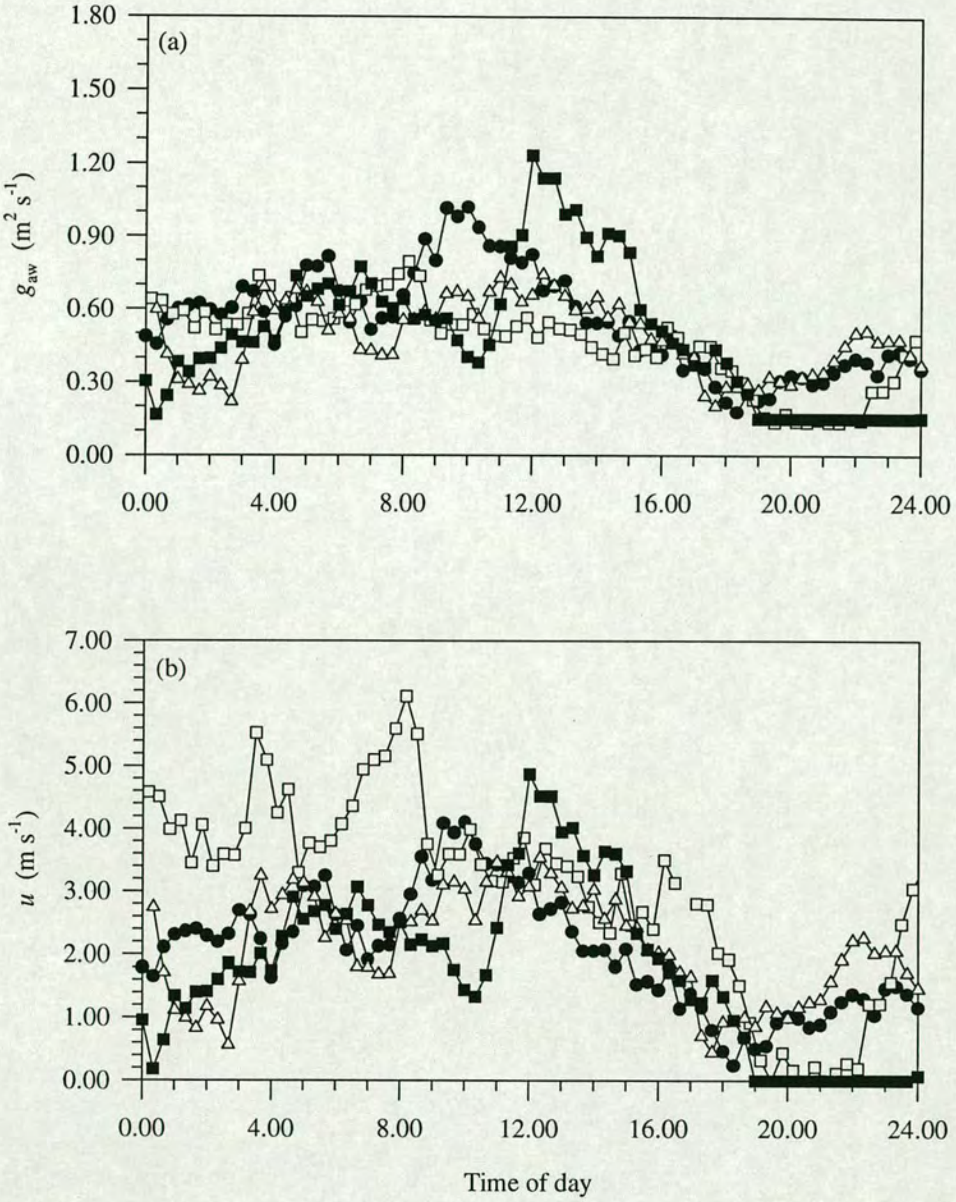


**Figure 6.1:** (a) Time courses of the aerodynamic conductance for heat transfer ($g_{aw}$) of *Azadirachta indica* windbreaks at Sadoré, Niger and (b) concurrent wind speed ($u$) on: DOY 283, 1992, in the early dry season (●); DOY 120, 1993, in the late dry season (□); DOY 198, 1993, in the middle of the rainy season (△); and DOY 264, 1993, in the late rainy season (■).

**Table 6.1**: Projected leaf area ($A_t$) of the trees in double-row *Azadirachta indica* windbreaks instrumented during four seasons of 1992 and 1993 for the determination of aerodynamic and surface conductances of windbreaks. $L_w$ is the linear leaf area density for the section of windbreak centred on the instrumented tree and $f_{tw}$ is the scaling factor used to convert values per tree to values per unit of windbreak length.

| Year | Season | Measurement Period (DOY) | $A_t$ ($m^2$) | $L_w$ ($m^2\ m^{-1}$) | $f_{tw}$ ($m^{-1}$) |
|---|---|---|---|---|---|
| 1992 | Early dry | 277-293 | 35.7 | 28.9 | 0.81 |
| 1993 | | | | | |
| | Late dry | 114-126 | 12.3 | 10.2 | 0.83 |
| | Mid rainy | 193-203 | 26.0 | 21.8 | 0.84 |
| | Late rainy | 260-271 | 55.8 | 39.5 | 0.71 |

$$\overline{g_s^{\max}} = \frac{g_{cw}^{\max}}{L_w}, \tag{6.18}$$

indicate that stomatal conductances were lowest in the late dry season, but reduced in the early dry season and late rainy season relative to the middle of the rainy season. Thus, it appears that the fall in $g_{cw}$ between the rainy season and the end of the dry season was the result of the combined effects of leaf loss and reductions in stomatal conductances in response to declining soil moisture reserves and increasing ambient vapour pressure deficits during the dry season.

Figure 6.2 also shows that the change in $g_{cw}$ during the course of each day followed a pattern that was common to all seasons. Typically, $g_{cw}$ reached a maximum during the early morning and then declined steadily throughout the day until sunset. In order to illustrate the probable cause of this pattern of response, the plot of $g_{cw}$ from DOY 283, 1992, is shown in Fig. 6.3 with concurrent plots of $D_a$ and $R_n$. In the early morning, $g_{cw}$ increased rapidly as illumination of the windbreaks, as reflected in values of $R_n$, increased while $D_a$ remained low. Values of $g_{cw}$ then declined during the remainder of the day in response to increasing $D_a$, in spite of high net radiation (and hence photon flux density) throughout the daylight period. Monteith (1995) argued that the apparent response of stomata to the vapour pressure deficit of air at leaf surfaces (Aphalo and Jarvis, 1991; Grantz and Meinzer, 1991; Gutiérrez *et al.*, 1994) occurs because leaves surrounded by drier

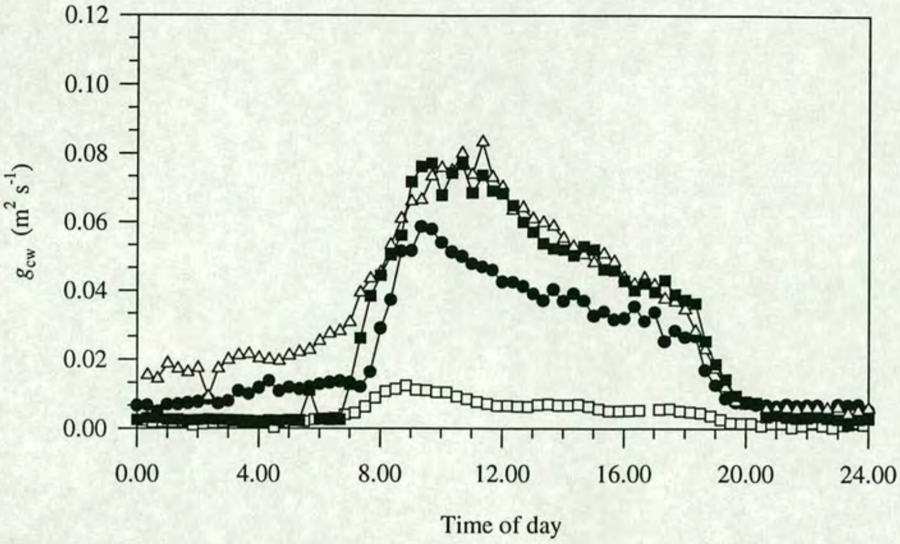


**Figure 6.2:** Time courses of the surface conductance ($g_{cw}$) for the canopies of *Azadirachta indica* windbreaks at Sadoré, Niger on: DOY 283, 1992, in the early dry season (●); DOY 120, 1993, in the late dry season (□); DOY 198, 1993, in the middle of the rainy season (△); and DOY 264, 1993, in the late rainy season (■).

air have higher rates of transpiration. The apparent response of $g_{cw}$ to the vapour pressure deficit of the bulk air suggests, therefore, that the ambient vapour pressure deficit drives evaporation from the surfaces of leaves in windbreak canopies and thus that windbreak canopies are well coupled to ambient air.

**Table 6.2**: Maximum surface conductance ( $g_{cw}^{max}$ ) per unit length of *Azadirachta indica* windbreaks and mean stomatal conductance ( $\overline{g_s^{max}}$ ) for one day from each of four seasons in 1992 and 1993.

| Year | Season | DOY | $g_{cw}^{max}$ ($m^2$ $s^{-1}$) | $\overline{g_s^{max}}$ (mm $s^{-1}$) |
|---|---|---|---|---|
| 1992 | Early dry | 283 | 0.059 | 2.0 |
| 1993 | Late dry | 120 | 0.012 | 1.2 |
| | Mid rainy | 198 | 0.084 | 3.8 |
| | Late rainy | 264 | 0.077 | 1.9 |

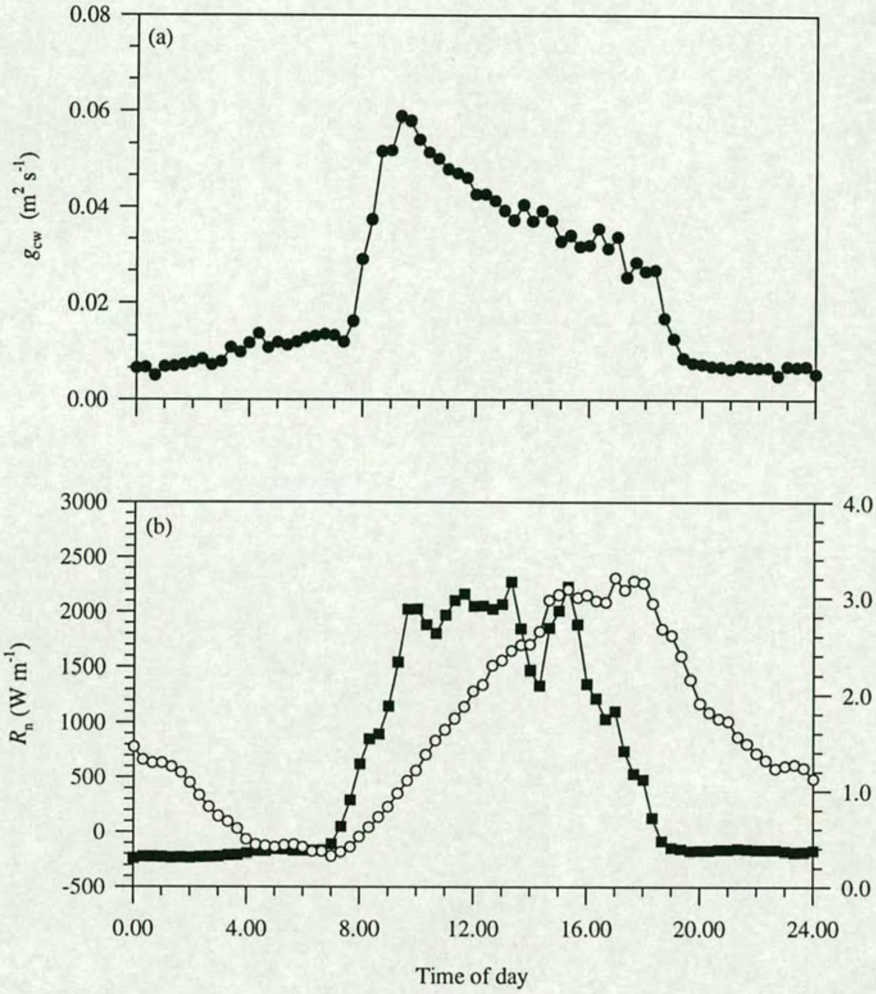


**Figure 6.3:** (a) Surface conductance ($g_{cw}$) of the canopy of an *Azadirachta indica* windbreak during DOY 283, 1992, at Sadoré, Niger and (b) concurrent net radiation ($R_n$) absorbed per unit length of windbreak (■) and ambient vapour pressure deficit ($D_a$) (○).

### **6.4.3** *Imposition of ambient vapour pressure at the surface*

When windbreaks are well coupled to the atmosphere, the ambient vapour pressure deficit is imposed at the surface of the canopy. Thus, the extent of coupling between windbreaks and the atmosphere can be assessed qualitatively by comparing the vapour pressure deficit at the surface of the canopy with $D_a$. It is less ambiguous, however, to compare the vapour pressures of ambient air and air at the surface because the influence of temperature on the comparison is then eliminated. The vapour pressure at the surface of the windbreak canopy, $e_{cs}$, was calculated, consequently, using Equation 6.7 for each period

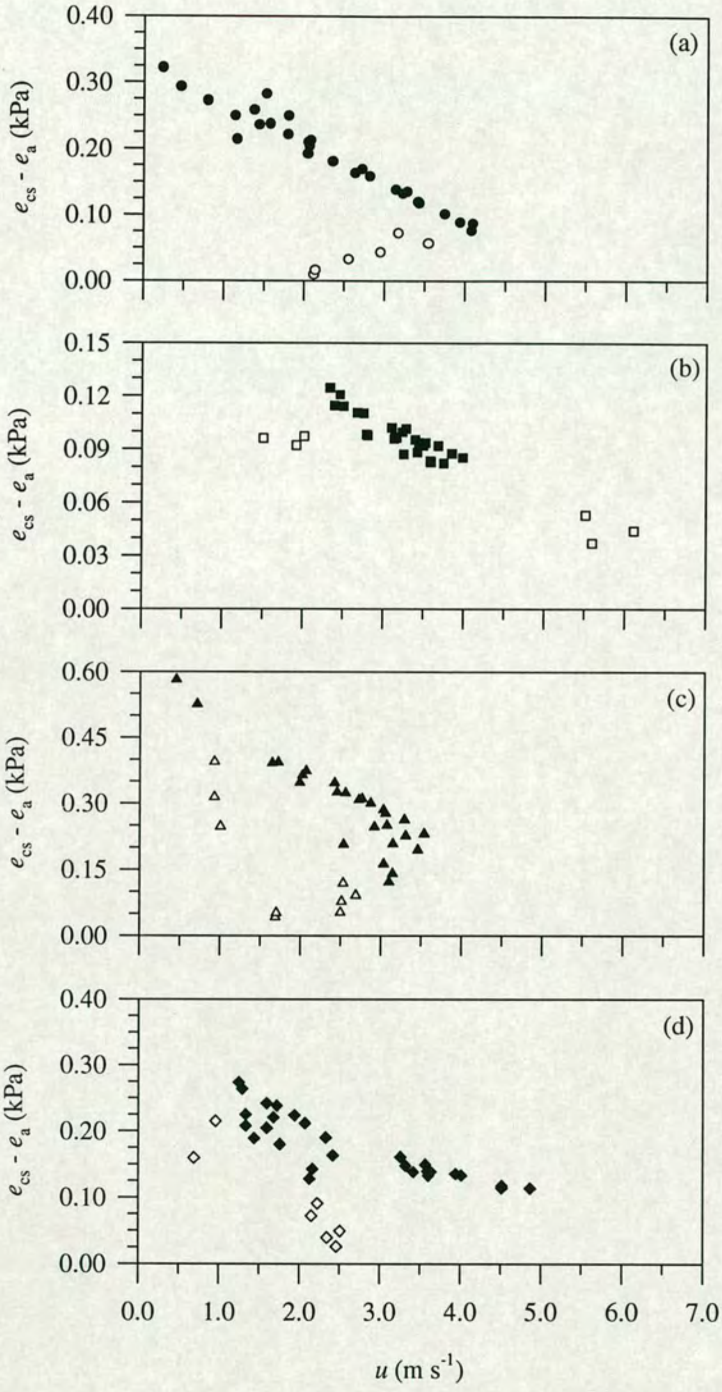


**Figure 6.4:** Influence of wind speed ($u$) on the difference between the vapour pressure of air at the surface of *Azadirachta indica* windbreak canopies ($e_{cs}$) and ambient vapour pressure ($e_a$) during daylight hours on: (a) DOY, 283, 1992; (b) DOY 120, 1993; (c) DOY 198, 1993; and (d) DOY 264, 1993, where daylight hours are defined as the period when net radiation was positive. The open symbols mark data from close to sunrise and sunset when transpiration was low, so that $e_{cs}$ tended to approach $e_a$ because fluxes of vapour from the canopy were low rather than the effect of wind speed.

of measurement and compared to the ambient vapour pressure, $e_a$, over a range of wind speeds on one day from each season (Fig. 6.4). At low $u$, $e_{cs}$ and $e_a$ diverged because aerodynamic conductances were low, so that vapour fluxes from the surface caused $e_{cs}$ to increase. As wind speeds increased, $e_{cs}$ and $e_a$ converged because aerodynamic conductances are enhanced at higher $u$, so that eddies in the ambient atmosphere penetrate the windbreak more easily and more frequently, replacing air at the surface with ambient air. Thus, at higher wind speeds, fluxes of vapour from the canopy surface had less influence on $e_{cs}$ because air was unlikely to be resident at the surface for sufficient time to begin to equilibrate with fluxes from the surface. Consequently, Fig. 6.4 shows the improvement in coupling between windbreaks and the atmosphere as wind speeds increase.

In Chapter 5, it was shown that the energy budgets of windbreaks are strongly influenced by advection and vertical entrainment because these processes cause ambient air with a non-equilibrium vapour pressure deficit to be delivered to canopy surfaces by turbulent motions in the atmosphere (McNaughton, 1976b; McNaughton and Spriggs, 1986). The data presented in Fig. 6.4 show, however, that the effects of advection and entrainment on windbreaks are reduced at low wind speeds because the imposition of ambient air at the surface is then impeded by low aerodynamic conductances.

### 6.4.4 $\Omega$ *values*

Values of $\Omega$ express the extent of coupling between the canopy and the atmosphere quantitatively on a relative scale between 0, when coupling is complete, and 1, when decoupling is complete. Thus, the improvement in coupling at higher wind speeds evident in Fig. 6.4 is also apparent from the decline in values of $\Omega$ as $u$ increased, as shown in Fig. 6.5, where $\Omega$ values from the daylight period of one day from each season are plotted against wind speed. Even at low wind speeds, however, values of $\Omega$ for the windbreaks never exceeded 0.5 and so decoupling of windbreaks from ambient air was never severe. Values of $\Omega$ approached 0.5 only at $u<1.0$ m s$^{-1}$ and, at moderate wind speeds, $\Omega$ was $\approx 0.3$ in all seasons except the late dry season, when it was usually close to 0.1 (Fig. 6.5). Because low wind speeds are not often encountered in the Sahelian environment, except for short periods in the late afternoon near sunset (Fig. 6.1b), windbreaks can be expected to be well coupled to ambient air, and therefore have good physiological control of transpiration, during much of the day at all times of year. The influence of advection and entrainment on the energy budget of windbreak canopies is thus reduced because of poor coupling during only a small proportion of the day.

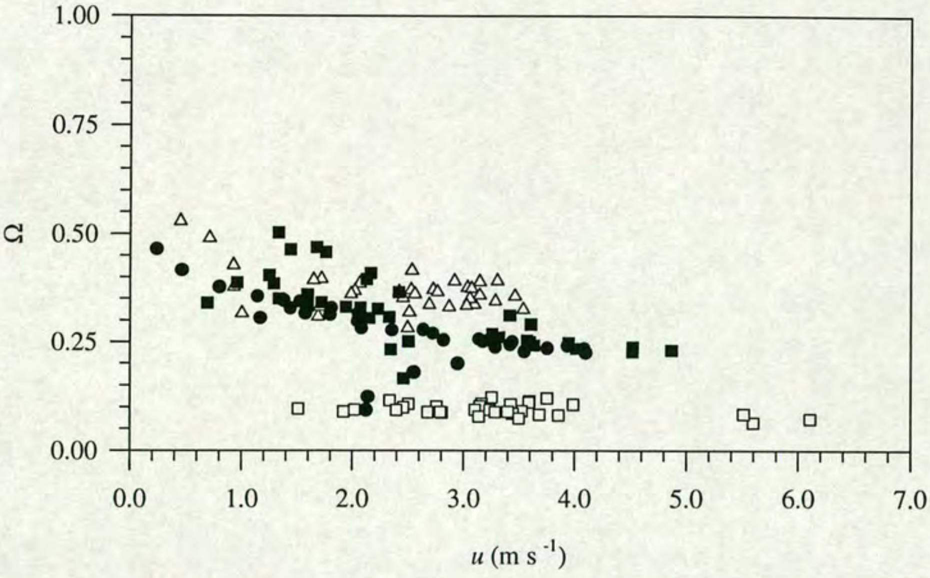


**Figure 6.5:** Response of the decoupling coefficient, Ω, to wind speed ($u$) for windbreaks of *Azadirachta indica* at Sadoré, Niger, during daylight hours on: DOY, 283, 1992, in the early dry season (●); DOY 120, 1993, in the late dry season (□); DOY 198, 1993, in the middle of the rainy season (△); and DOY 264, 1993, in the late rainy season (■). Values are means for periods of 20 min.

The data in Fig 6.5 are re-plotted against $g_{aw}$ in Fig 6.6, together with lines showing the response of Ω to $g_{aw}$ at a range of values of $g_{cw}$. Comparison of the data points with the lines in Fig 6.6 shows that changes in Ω within any day resulted from proportionally larger variation in $g_{aw}$ than $g_{cw}$, so that the ratio $g_{aw}/g_{cw}$ increased as $g_{aw}$ increased, causing Ω to decrease (Equation 6.12). Because $g_{aw}$ varied with $u$ (Fig. 6.1), the response in Fig. 6.5 of Ω to $u$ was thus caused by increases in $g_{aw}/g_{cw}$ at high wind speeds. Similarly, the very low values of Ω observed in the late dry season occurred because values of $g_{cw}$ were much lower in this period than at other times of year (Fig. 6.2), while $g_{aw}$ values were similar in magnitude in all seasons (Fig. 6.1), so that $g_{aw}/g_{cw}$ was high. Thus, the reduction in $g_{cw}$ in the late dry season resulting from leaf loss and stomatal responses to the aridity of the environment caused coupling between the windbreaks and the atmosphere to be enhanced. Others have similarly observed that stresses which lower surface conductances generally reduce Ω in all types of vegetation and result in increased coupling and improved physiological control of transpiration (Meinzer and Grantz, 1989; Kelliher *et al.*, 1993).

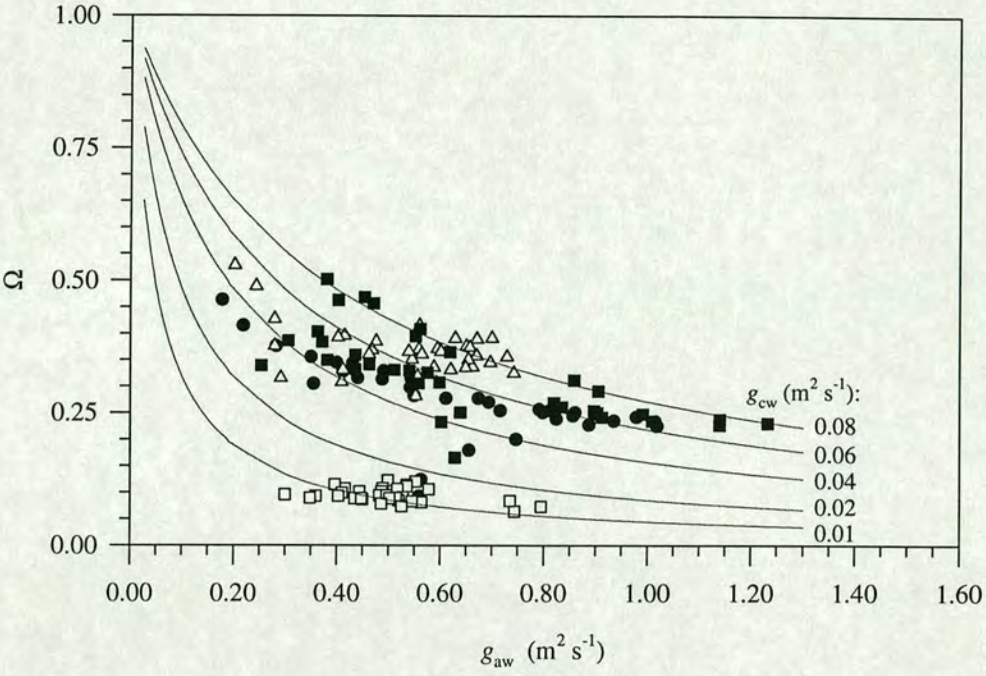


**Figure 6.6:** Response of the decoupling coefficient, Ω, to the aerodynamic conductance ($g_{aw}$) of windbreaks of *Azadirachta indica* at Sadoré, Niger, during daylight hours on: DOY, 283, 1992, in the early dry season (●); DOY 120, 1993, in the late dry season (□); DOY 198, 1993, in the middle of the rainy season (△); and (d) DOY 264, 1993, in the late rainy season (■). The lines show the response of Ω to $g_{aw}$ at a range of values of $g_{cw}$, the surface conductance of the windbreak canopy. (The course of the lines was determined with Equation 6.12 using ε at 30 °C.)

Values of Ω tend to be low for types of vegetation that are tall and aerodynamically rough, such as forests, and high for vegetation that is uniformly short and smooth, such as field crops in monoculture. Jarvis and McNaughton (1986) gave values of Ω for unstressed grassland of 0.8 and for unstressed forests of ≤0.2. Similarly, Meinzer and Grantz (1989) determined values of Ω of ≈0.8 for an unstressed sugarcane (*Saccharum* spp.) crop and Köstner *et al.* (1992) found that Ω for the upper part of the canopy of a deciduous forest varied between 0.05 and 0.35. Coupling of windbreaks to the ambient atmosphere is therefore similar to the atmospheric coupling of forests, but contrasts sharply with the poor coupling of crops, especially those sheltered by windbreaks (McNaughton, 1983, 1988). As a consequence, the environmental and physiological variables controlling transpiration by windbreak trees and adjacent crops are different.

### **6.4.5** *Environmental control of transpiration by windbreaks*

Figure 6.7 shows transpiration by the windbreak and concurrent values of $R_n$, $D_a$ and $\Omega$ for one day from the early dry season, 1992. $\Omega$ increased steadily over the course of the day from near 0.2 soon after sunrise to over 0.4 just before sunset, so that coupling declined throughout the day. In the morning, $E$ increased smoothly as $D_a$ became higher, but did not respond to fluctuations in $R_n$. Later in the day, fluctuations in $R_n$ elicited coincident fluctuations in $E$, although the changes in $E$ were proportionately much smaller than the changes in $R_n$. Thus, as $\Omega$ increased and coupling declined, environmental control of transpiration shifted from $D_a$ towards $R_n$, so that, from Equations 6.8 and 6.10, $E$ shifted away from $E_{imp}$ towards $E_{eq}$. However, because decoupling was never very severe and $\Omega$ was never very high, the influence of $R_n$ on transpiration by the trees was always small relative to the influence of $D_a$ (Equation 6.11). In contrast, because of the high $\Omega$ values expected for a sheltered crop (McNaughton, 1988), transpiration by crops adjacent to windbreaks is controlled predominantly by net radiation, with much less effect of $D_a$.

Similar data from a day from the late dry season of 1993 are plotted in Fig. 6.8. Values of $\Omega$ were close to 0.1 throughout the day, indicating that coupling between the windbreak and the atmosphere was very close. There was, consequently, virtually no influence of $R_n$ on transpiration by the trees at any time and, from Equation 6.11, $E$ was close to $E_{imp}$, so that the environmental variable with most influence on $E$ was $D_a$ (Equation 6.8). However, despite the increase in $D_a$ from near 2.0 kPa in the early morning to almost 6.0 kPa in the late afternoon, there was no concurrent increase in $E$ because $g_{cw}$ declined over the course of the day (Fig. 6.2), counteracting the rising evaporative demand of the atmosphere. The very close coupling of the windbreaks to the atmosphere at the end of the dry season thus enabled the trees to exert tight physiological control over transpiration.

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

Transpiration by well-coupled vegetation tends towards the imposed rate because the ambient vapour pressure deficit is imposed at the surface. Equation 6.8 shows that $E_{imp}$ changes in proportion to changes in surface conductances, so that when vegetation is closely coupled to the atmosphere and $D_a$ is imposed at the surface, plants are able to

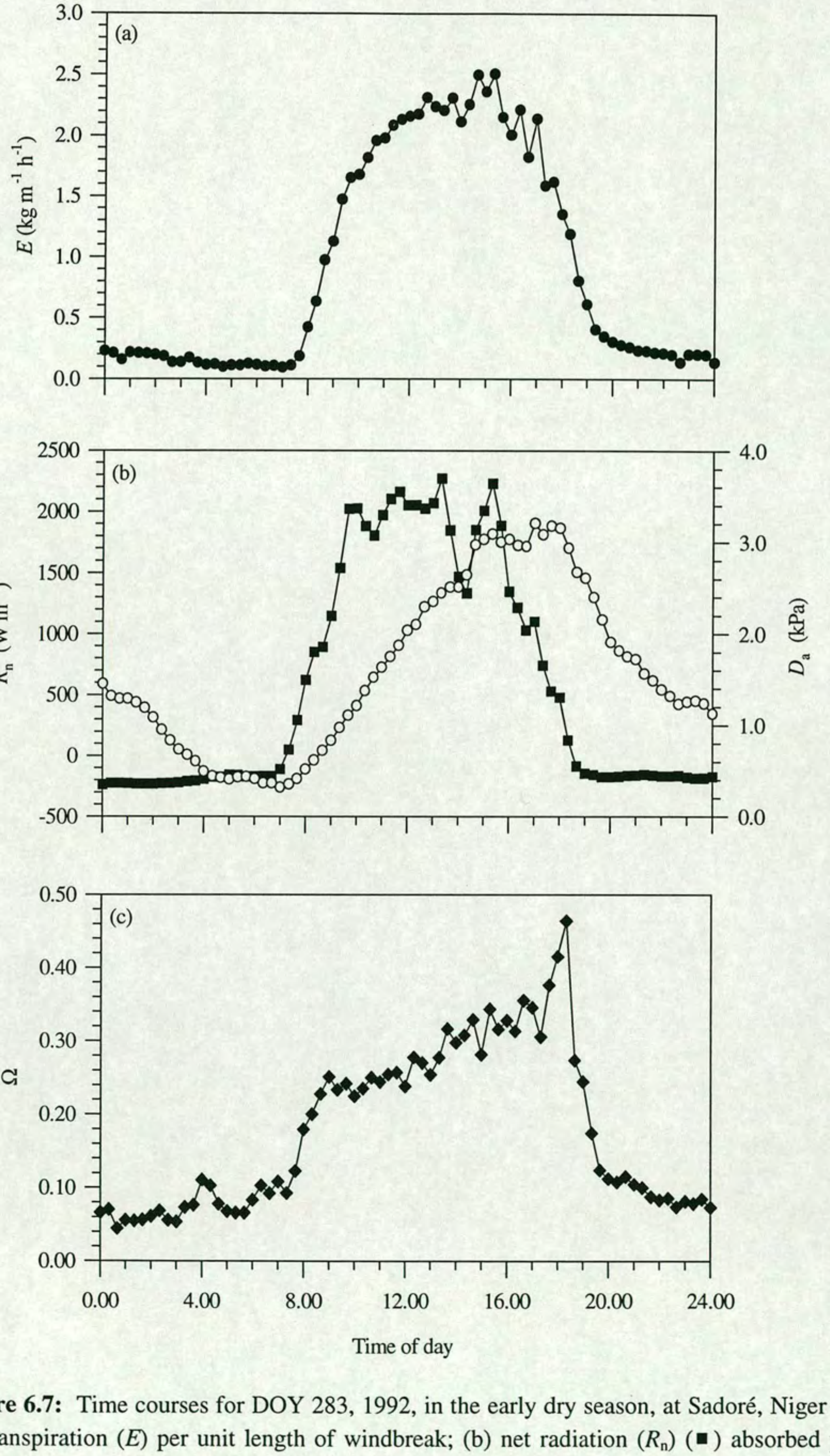


**Figure 6.7:** Time courses for DOY 283, 1992, in the early dry season, at Sadoré, Niger of: (a) transpiration ($E$) per unit length of windbreak; (b) net radiation ($R_n$) (■) absorbed per unit length of windbreak and ambient vapour pressure deficit ($D_a$) (○); and (c) the decoupling coefficient, Ω.

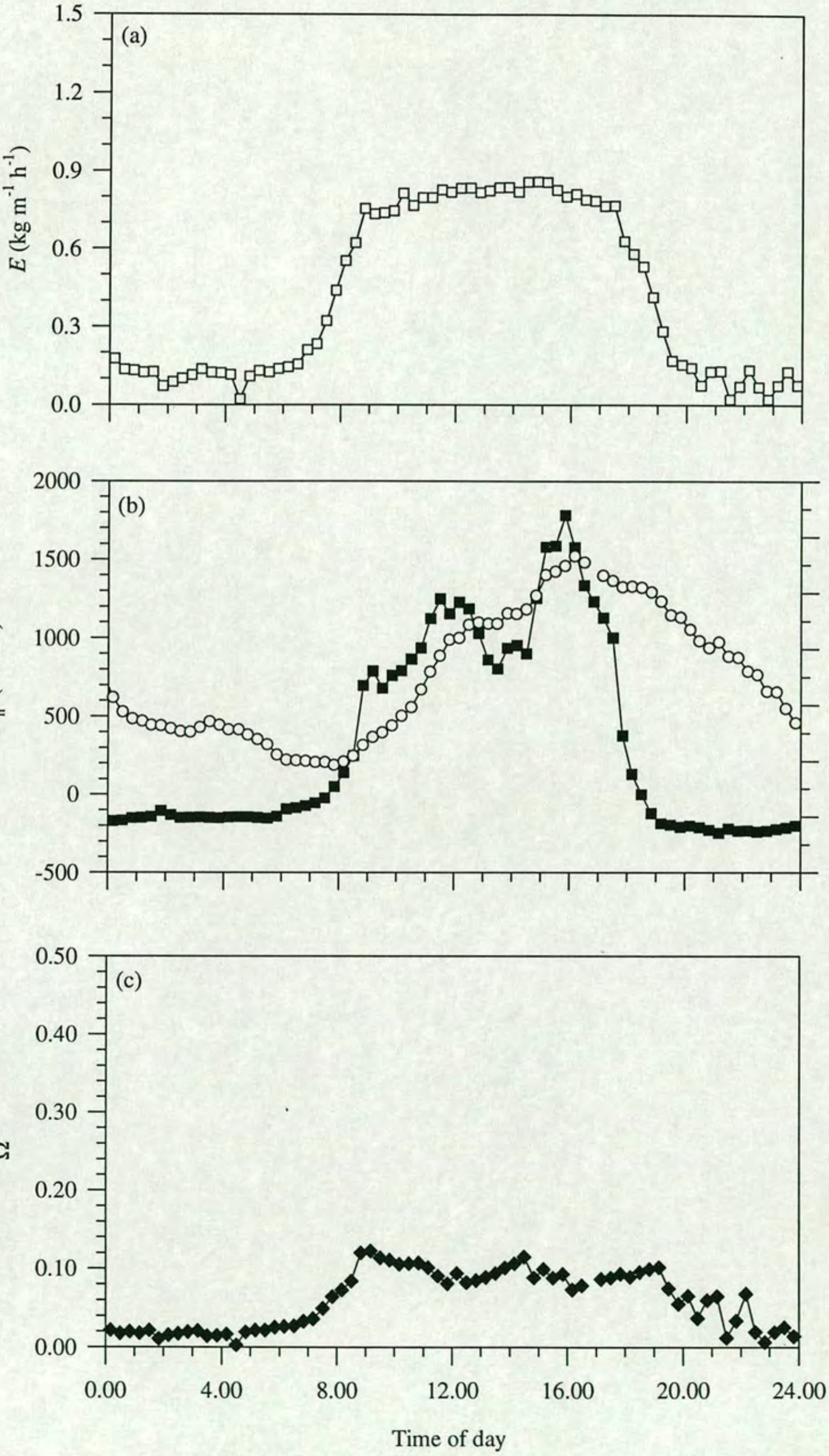


**Figure 6.8:** Time courses for DOY 120, 1993, in the late dry season, at Sadoré, Niger of: (a) transpiration (*E*) per unit length of windbreak; (b) net radiation ($R_n$) (■) absorbed per unit length of windbreak and ambient vapour pressure deficit ($D_a$) (○); and (c) the decoupling coefficient, Ω.

regulate water loss by adjusting the surface conductance. Thus, the generally low values of $\Omega$ found demonstrate that windbreaks are able to control transpiration effectively through physiologically-mediated responses of surface conductance to environmental stresses, although because $\Omega$ was never 0, physiological control of transpiration by windbreaks is never perfect and fractional changes in $g_{cw}$ cause proportionately smaller fractional changes in $E$. The surface conductance of a canopy depends on leaf area and stomatal conductances of leaves in the canopy (McNaughton and Jarvis, 1983; Kelliher *et al.*, 1995) and so windbreak trees can reduce water use by either closing their stomata or, during the dry season or drought, by shedding leaves.

Good physiological control over transpiration ensures that windbreak trees are able to regulate their demand for water to suit the availability of moisture from the soil. During the Sahelian rainy season, dry spells are common (Sivakumar *et al.*, 1993) and so the availability of soil water for uptake may, at times, be temporarily reduced. If the demand for water driven by ambient microclimate cannot be met by uptake of water from the soil during such dry periods, windbreak trees can adjust stomatal conductances downwards until uptake of water by the roots is able to satisfy demand. In contrast, when the surface conductance of a crop sheltered by a windbreak declines in response to drying of the soil during a dry spell, demand for water by the crop is relatively unchanged because sheltered crops are poorly coupled to ambient air and so have poor physiological control over transpiration. Thus, when dry spells occur in the Sahel, windbreak trees are able to conserve available water for longer than leeward crops and so windbreaks have a better chance of avoiding damaging stresses.

It is during dry spells that moisture stress in crops is most likely to be exacerbated by competition for water between windbreak trees and the crop. Simulation models designed to predict the influence of competition on the productivity of windbreak systems must, therefore, accurately represent the response of both trees and crops to moisture stress and so they must properly account for the differences in the extent to which each is able to exert physiological control over their demand for water. Because physiological control of water use depends on the ratio of aerodynamic to surface conductances, this can be accomplished in a process-based simulation by modelling the aerodynamic and surface conductances of windbreaks and sheltered crops independently.

During the long Sahelian dry season or when dry spells lengthen into droughts, *A. indica* trees in windbreaks can further reduce surface conductances and their demand for water by shedding leaves. As the values of $\Omega$ determined in the late dry season showed, leaf shedding also serves to enhance coupling of windbreaks to the atmosphere and so gives the trees very close control over water loss. Thus, leaf shedding in response to severe reductions in the availability of moisture from the soil helps *A. indica* trees in windbreaks to minimise their demand for water and ensures that they have excellent control of water loss during the driest periods of the year.

### **6.4.7** *Regulation of the influence of advection on windbreak*

Transpiration can be enhanced or depressed relative to the equilibrium rate by advection and entrainment because the imposition of $D_a$ at the surface of the canopy drives $E$ towards $E_{imp}$ and away from $E_{eq}$. Advection and entrainment enhance transpiration when $D_a>D_{eq}$ because the imposed rate of transpiration is then higher than the rate at equilibium, but when $D_a<D_{eq}$, transpiration is depressed by advection and entrainment because the transpiration rate at equilibrium is then higher than when $D_a$ is imposed at the surface (McNaughton, 1976b; McNaughton and Jarvis, 1983). Thus, when the ratio $D_{eq}/D_a$ has a value of <1.0, advection and entrainment will enhance transpiration, but when $D_{eq}/D_a$ >1.0, advection and entrainment will depress transpiration.

Data presented in Chapter 5 demonstrated that advection and entrainment exert considerable influence on water use by windbreaks in the Sahel. Figure 6.9 shows the ratio $D_{eq}/D_a$ for one day from each of the late dry season and the middle of the rainy season, 1993, and demonstrates, as discussed in Chapter 5, that advection and entrainment mainly enhanced transpiration in the middle of the rainy season but depressed transpiration in the late dry season. Advection and entrainment enhanced transpiration in the more humid conditions of the rainy season because $g_{cw}$ was high (Fig. 6.2), with the result that, from Equation 6.9, $D_{eq}$ and the evaporative demand of the atmosphere at equilibrium was low, so that the imposition of $D_a$ at the windbreak surface by turbulent motions in the atmosphere tended to enhance transpiration. In the late dry season, however, $g_{cw}$ was very low (Fig. 6.2), so that $D_{eq}$ was very high and tended to be higher than $D_a$, with the result that advection and entrainment depressed transpiration. The surface conductance of windbreaks consequently controls not only transpiration, but also regulates the magnitude and sign of the influence of advection and entrainment on water use by the trees.

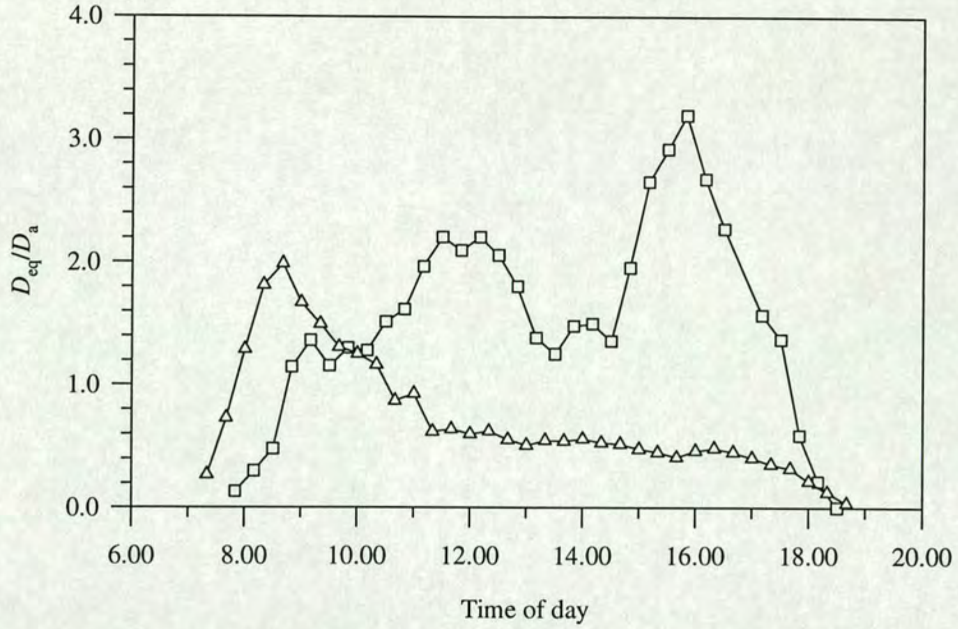


**Figure 6.9:** The ratio $D_{eq}/D_a$ at Sadoré on DOY 120, 1993 ( □ ), in the late dry season, and DOY 198, 1993 ( △ ), in the middle of the rainy season, where $D_{eq}$, calculated using Equation 6.9, is the equilibrium vapour pressure deficit for windbreaks of *Azadirachta indica* and $D_a$ is the ambient vapour pressure deficit.

## 6.5 Management of demand for water by windbreak trees

The analysis of the aerodynamic and surface conductances of windbreaks presented here has shown that close coupling of windbreaks to the atmosphere provides windbreak trees with good physiological control of transpiration. A corollory of this is that management interventions designed to reduce the surface conductances of windbreak canopies will be effective in reducing demand for water by windbreaks. Consequently, at locations where agriculturalists or land-use planners in the Sahel fear that competition for water by windbreak trees will adversely affect yields of adjacent crops, steps can be taken to reduce the surface conductances of the trees in order to reduce the amount of water used by the trees and, therefore, the impact of competition on the crops. Because the surface conductance of a plant canopy can be regarded, approximately, as the parallel sum of the stomatal conductances of individual leaves, values of $g_{cw}$ for windbreaks can be reduced by either reducing stomatal conductances or by reducing leaf areas. Managers can reduce stomatal conductances by choosing tree species for inclusion in windbreaks that tend to have lower stomatal conductances than other species and they can reduce leaf areas in windbreaks by pruning the trees.

It was shown in Chapter 2 that tree species growing in windbreaks which use less water tend to have lower stomatal conductances, when measured with a porometer, than species which take up larger amounts of water. Close coupling of windbreak canopies with ambient air confirms, therefore, that comparisons of the relative magnitudes of stomatal conductances among tree species can be used as an indicator of relative water use when trying to select species on the basis of water requirements. A survey of stomatal conductances of species suitable for use in windbreaks in the Sahel would consequently be useful to development agents and land-use planners trying to select species for new windbreak plantings. Measurements would need to be made on trees with $\Omega$ coefficients similar to those found for trees in windbreaks and the response of stomatal conductances in each species to environmental conditions should be determined. Together with information on typical leaf area densities of each species, such data could be used to rank species for relative demand for water.

Pruning of windbreaks in the Sahel to reduce their demand for water and, hence, their competitive influence on neighbouring crops has been suggested previously by van den Beldt (1990) and close coupling of windbreaks to the atmosphere suggests that use of pruning for this purpose should be successful. The influence of changes in leaf area on surface conductances of windbreaks may be attenuated, however, by adjustments in stomatal conductances following pruning. When leaf area of a windbreak is reduced by pruning, leaf water potentials may increase in response to the consequent fall in the flux of water between the soil and the canopy (Jarvis, 1976), causing stomatal conductances to increase, so that the surface conductance of the windbreak tends back towards the level that existed prior to pruning. Consequently, pruning probably does not induce decreases in transpiration rates that are proportional to the fraction of leaf area removed during pruning. Research should therefore investigate changes in the water relations of windbreak trees in the Sahel in response to pruning in order to determine the species and environmental conditions in which pruning is most effective in reducing demand for water.

Historically, the primary reason for establishing windbreaks in the Sahel has usually been control of wind erosion (Onyewotu, 1983; Michels, 1994). Any management strategies that advocate pruning of windbreaks must, consequently, ensure that protection of the soil is maintained after pruning, so that the goal of pruning windbreaks should be to maximise control of wind erosion while minimising use of water by the trees at locations where competition between trees and crops for water is thought to be a problem. It may be possible, for example, to reduce the leaf area and surface conductance of windbreak canopies while minimising the loss of shelter by pruning windbreaks to conform to an optimum shape. For instance, a tall canopy with a narrow cross-section can be expected to shelter a larger area than a short, broad canopy, but have a similar leaf area and use a similar amount of water. Changes in the porosity of windbreaks as a result of pruning can also be expected to influence the effectiveness of shelter created by windbreaks. Further studies are required, therefore, to determine the best approach to pruning windbreaks that ensures protection of soils is maintained while competition is reduced.

## 6.6 Conclusions

Surface conductances for canopies of *A. indica* windbreaks were always small relative to the magnitudes of aerodynamic conductances, so that, at all times of year, the windbreaks studied were well coupled to the ambient atmosphere and had good physiological control over transpiration. Values of the decoupling coefficient, $\Omega$, varied with fluctuations in wind speed and as a result of the sharply lower surface conductances of the windbreaks in the latter part of the Sahelian dry season. In the driest period of the year, $\Omega$ was $\approx 0.1$, indicating that when the availability of soil moisture was most limited, the trees were able to exert very tight control over water loss as a result of reductions in surface conductances caused by leaf shedding and stomatal closure. Physiological control of transpiration remained good during more humid periods of the year, when $\Omega$ was close to 0.3 at moderate wind speeds. Good physiological control of transpiration by windbreak trees implies that management strategies designed to reduce the surface conductances of windbreak canopies should be effective in reducing demand for water by windbreaks. Thus, practices such as pruning and utilisation of tree species with relatively low stomatal conductances should help to alleviate competition for water between windbreaks and adjacent crops.

Because windbreaks are closely coupled to the atmosphere, transpiration by trees in windbreaks is driven by the imposition of ambient air at the surface of the canopy. Consequently, as shown in Chapter 5, advection and vertical entrainment have a strong influence on water use by windbreak trees, although the influence of these processes declines at low wind speeds because coupling is then reduced. More usually, however, wind speeds in the Sahel are not low and so the generally low values of $\Omega$ found for windbreaks demonstrate that the environmental variable with most influence on transpiration by windbreak trees is the ambient vapour pressure deficit. In contrast, transpiration by crops sheltered by windbreaks can be expected to be controlled primarily by net radiation because sheltered crops are poorly coupled to overlying air (McNaughton, 1988).

Poor coupling implies that sheltered crops are less able than windbreak trees to exert physiological control over transpiration. Demand for water by windbreaks and crops is affected differently, therefore, when the availability of soil moisture is reduced, so that the disparity in atmospheric coupling between windbreaks and crops is an important mechanism controlling the partitioning of water between trees and adjacent crops during dry spells. Differences between trees and crops in the extent of coupling must be adequately modelled, therefore, if the influence of competition for water on tree and crop growth in windbreak systems is to be accurately simulated. Modellers can account for differences in atmospheric coupling between windbreaks and crops by ensuring that the aerodynamic and surface conductances of each are simulated independently. Poor coupling of sheltered crops suggests, however, that it is most important to simulate absorption of net radiation accurately in models of water use by crops behind windbreaks. Good coupling implies, conversely, that accurate representation of net radiation absorption by windbreaks is much less important when simulating water use by windbreak trees than reliable reference data for ambient vapour pressure deficit and sound modelling of the response of the surface conductance to environmental variables.

# Chapter 7

# Conclusions and Recommendations

## 7.1 Summary of findings

The research undertaken over the course of this project sought to determine how water use by windbreak trees influences where crop productivity can benefit from the establishment of windbreaks. Experiments were done to determine how much water windbreak trees use, where it is taken from and which environmental and physiological variables control water use by windbreak trees, so that the circumstances in which competition for water between windbreak trees and crops is most severe could be identified. Measurements of water use by windbreak trees showed that the amount of water transpired by windbreaks varies among species, so that the influence of windbreaks on crop productivity depends on the competitiveness of the trees species utilised in the windbreaks. The potential competitiveness of trees also depends on the extent to which lateral roots extend into the cropped area of fields and extract water from the surface layers of the soil. Thus, *Azadirachta indica* was shown to be less competitive than either *Acacia holosericea* or *Acacia nilotica* because it transpires less water and extracts less moisture from the rooting zone of nearby crops.

The impact of water use by windbreak trees on crop productivity was also shown to depend on the accessibility to trees of groundwater or other deep reserves of soil moisture. Uptake of water from these sources by windbreak trees reduces the quantity of water they remove from the rooting zone of the crop during dry periods and so probably reduces the severity of drought stress suffered by sheltered crops when water is in limited supply. Thus, at locations where trees have access to groundwater, crop yields likely benefit more from shelter than at locations where they must compete with the crop for water stored in the surface layers of the soil profile.

The quantity of water used by windbreaks was shown from measurements of the energy budgets of windbreak canopies in the Sahel to be strongly influenced by advection and vertical entrainment, which can either enhance or depress transpiration from windbreak trees, depending on the surface conductance of the windbreak canopy. These measurements were made possible, in part, by development of methods for determining the aerodynamic conductances of vegetation that is not horizontally extensive. Combining use of heated leaf-replica pairs to measure leaf boundary layer conductances with measurements of the bulk aerodynamic conductances of whole trees showed that aerodynamic conductances for a whole tree can be estimated from *in situ* measurements of leaf boundary layer conductances; but only if the conductance for transfer from the outer limits of leaf boundary layers to air outside the crown of the tree is accounted for and summed in series with the boundary layer conductances for the leaves of the crown. Aerodynamic conductances determined in this way made closure of the energy budget for windbreak canopies possible by enabling sensible heat fluxes to be calculated independently of other components of the energy budget, from measurements of leaf temperatures. Use of this approach should permit energy budgets of trees in agroforestry to be measured more widely.

Analysis of the aerodynamic and surface conductances of windbreak canopies demonstrated that windbreaks are well coupled to the ambient atmosphere, so that transpiration by windbreak trees is controlled primarily by the ambient vapour pressure deficit and the surface conductance of the canopy. Windbreak trees consequently have good physiological control over transpiration and so are able to moderate their use of water when the availability of moisture becomes limited.

## 7.2 The severity of competition between windbreaks and crops

The impact of windbreaks trees on adjacent crops as a result of competition for water is governed by supply and demand. Competition is likely to be most severe where windbreak trees have a high demand for water that can only be supplied from the surface layers of the soil because no other sources of water are accessible. Consequently, in assessing how water use by windbreaks will affect crop productivity at a particular location in the Sahel, land-use planners must evaluate how much water windbreak trees are likely to demand and from where it is likely to be supplied. If it is thought that windbreak trees will extract large amounts of water from the rooting zone of the crop, planners should recommend management strategies to farmers and development agents that will reduce the degree of interference by the trees, or recommend that windbreaks are not suitable for the site and that other systems of land-use management should be considered. The basis for such decisions should be an understanding of the variables which determine demand for water by windbreaks and sources of supply from the environment.

### **7.2.1** *Demand for water by windbreaks*

The quantity of water demanded by windbreaks depends on the properties of ambient air and the characteristics of the windbreak canopy. Partitioning of radiant energy absorbed by windbreaks into transpiration and convective heat loss depends largely on the evaporative demand of the ambient atmosphere and the surface conductance of the canopy. Trees in windbreaks are openly exposed to atmospheric turbulence because they are generally taller than vegetation covering surrounding surfaces, so that turbulent motions in the atmosphere easily penetrate windbreak canopies and, as a result of advection and vertical entrainment, impose air with a non-equilibium vapour pressure deficit at leaf surfaces. The ambient vapour pressure deficit thus drives evaporation from the surfaces of leaves of windbreak trees, but the magnitude of the surface conductance determines whether advection and entrainment enhance or depress transpiration because stomatal responses to environmental conditions are able to regulate water use by windbreaks effectively.

Demand for water by windbreaks is consequently higher when the ambient vapour pressure deficit is high and when the surface conductance of the windbreak canopy is high. Ambient vapour pressure deficits cannot be controlled and so efforts to manage the amount of water demanded by windbreaks should be directed towards controlling the surface conductances of the trees. The surface conductance of a windbreak canopy is closely proportional to the stomatal conductances of leaves in the canopy and the linear leaf area density of the windbreak. Consequently, management strategies for controlling water use by windbreaks must seek to control the leaf area of the trees or the stomatal conductance of leaves in the canopy, either by pruning or selection of species that tend to have low stomatal conductances relative to other species.

### **7.2.2** *Supply of water to windbreaks*

The source of water used by windbreak trees depends on the characteristics of their root systems and the availability of water from different parts of the soil profile. In Chapter 3, it was shown that windbreaks use groundwater or deep reserves of soil water, when it is accessible to tree roots, unless water is abundant near the surface. At sites where groundwater is accessible, therefore, competition for water between windbreaks and crops does not influence crop productivity greatly, unless the tree species has a root system that is confined to surface layers of the soil and spreads out widely into the crop. Where groundwater cannot be used by the trees, they must obtain all of the water they require from the top 2 to 3 m of soil, so that competition for water is likely to exacerbate stress in the crop resulting from drought or dry spells and thus increase the impact of shortages of water on crop yields. The severity of competiton at locations where groundwater is not accessible depends on the quantity of water demanded by the trees and the distance to which lateral roots extend into the crop. It is at these sites that management strategies for controlling water use by windbreaks are most important and most likely to enhance the response of crop productivity to shelter by windbreaks.

## 7.3 Strategies for managing water use by windbreak trees

### **7.3.1** *Selection of tree species for use in windbreaks*

One strategy for managing the demand for water by windbreaks is to select species on the basis of leaf area index and stomatal conductances expected under the climatic conditions which prevail at a proposed site. Data presented in Chapter 2 showed that differences exist among species planted in windbreaks in the total amount of water used and that a principal cause of these differences was disparities among species in the magnitude of stomatal conductances. Results in Chapter 6 demonstrated substantial physiological control of transpiration from windbreaks and so provided a rational, physical basis for selecting species on the basis of their stomatal conductances. A survey comparing stomatal conductances among species thought to be suitable for use in windbreaks in the Sahel should, therefore, produce information that can be used by land-use planners to select tree species on the basis of probable relative water use. The advantage of such a study over more comprehensive investigations of water use by each species is that it could be completed more quickly and more cheaply and include a larger number of species.

Information on differences in rates of leaf area development and maximum leaf area indices among species should also be compiled from such a survey. This would enable land-use planners to select, for example, species with lower stomatal conductances and lower leaf area densities for use at locations where it is thought that use of a large amount of water by windbreaks is likely to be deleterious to crop growth. These data could then also be used to parameterise models of water use by windbreaks for different species and combinations of species.

Another important criterion when selecting tree species for use in windbreaks is the tendency of their root systems to spread laterally in the surface layers of the soil, because, as shown in Chapter 2, tree species with roots capable of extracting water from near the soil surface in the cropped area of fields can drastically reduce the availability of water to the crop. This is a very important consideration at sites where trees do not have access to groundwater and so must rely, like the crop, on water from the top of the soil profile. It may also be important for some species at sites with shallow water tables because there may be tree species whose root systems are confined to shallow layers of the soil, so that they cannot utilise groundwater even if it is relatively close to the surface. Land-use planners would therefore benefit from a compilation of information about the rooting habits of tree species suitable for the Sahel. This information would need to be collected at alternative sites with shallow and deep groundwater to assess whether species can utilise groundwater where it is accessible, as well as the lateral spread of roots where groundwater is not accessible.

Observations made in this project indicate that *A. indica* is ideally suited to use in windbreaks in the Sahel because it does not compete strongly with nearby crops. *A. indica* has lower stomatal conductances and uses less water than other species (Chapter 2); it is able to utilise groundwater or deep reserves of soil water within at least 8 m of the soil surface (Chapter 3); and when groundwater is not accessible, it extracts less water through lateral roots than other tree species potentially used in windbreaks (Chapter 2). These characteristics may account for the popularity of *A. indica* for use in windbreaks in the Sahel. The range of useful products from *A. indica* is limited, however, and because people in the Sahel have uses for products from many tree species, it is important that a wide diversity of species are utilised in agroforestry in the Sahel. Furthermore, widespread reliance on only a few species leaves production systems vulnerable to severe damage from insects and diseases. Thus, further studies of the rooting and canopy characteristics of trees adapted to Sahelian conditions are desirable in order to identify other tree species that are similarly suitable for use in windbreaks or may be suitable if management strategies are employed to control their demand for water.

### **7.3.2** *Pruning of windbreak canopies*

Another strategy for reducing demand for water by windbreak trees is to prune them in order to reduce the linear leaf area density and, consequently, the surface conductance of the canopy. Pruning a windbreak prior to the start of the cropping season, for example, would reduce the amount of water used by the windbreak during the initial stages of crop growth and delay demand of large amounts of water by the trees until the latter part of the cropping season or until after the crop has been harvested. It may be possible, therefore, to use pruning to improve the temporal complementarity of water use by windbreak trees and adjacent crops and create a situation akin to relay cropping where demands for resources by the trees almost follow after demands by the crop. Many different strategies can be imagined for pruning, but planners must be able to assess which are best-suited to conditions at a particular site. There is therefore a need to carry out agronomic trials of pruning practices at a range of locations in the Sahel and in association with a variety of cropping systems. These trials should test the impact on water use by windbreaks and crop productivity of pruning regimes with varying levels of severity at different times of the year.

Pruning windbreaks involves making compromises between controlling water use by the trees and maintaining the extent and effectiveness of shelter provided for the crop. It may be possible to reduce the leaf area and conductance of canopies while minimising loss of shelter by using pruning to create canopies with different shapes. For example a tall canopy with a narrow cross-section can be expected to shelter a larger area than a short, broad canopy, but have a similar leaf area and use a similar amount of water. Changes in the porosity of windbreaks as a result of pruning can also be expected to influence the effectiveness of shelter created by the windbreak. A study should therefore be undertaken to evaluate pruning strategies that minimise demand for water by windbreaks while the effectiveness of shelter is maximised.

### **7.3.3** *Pruning of tree root systems*

Brenner (1991) and Onyewotu *et al.* (1994) demonstrated that pruning of roots in the top 1 m of the soil profile can be used to reduce competition for water between windbreak trees and adjacent crops. Such a practice is, however, likely to be very labour-intensive in a region such as the Sahel, where mechanisation of agriculture is very poorly developed. Consequently, information on the relative water use and rooting habits of tree species suitable for use in agoforestry in the Sahel would be very valuable because it would enable land-use planners to assess with which species and at which locations labour invested in pruning of root systems is likely to be worthwhile.

## 7.4 A strategy for windbreak deployment in the Sahel

Many variables must be considered when deciding whether windbreaks are suitable for specific locations in the Sahel. Planners must try to satisfy needs within local communities for crop products (grain, stover, fodder) and tree products (fruit, leaves, wood, fodder) while not upsetting the ecology of the area by practices which, for example, exacerbate soil erosion, increase run off, promote pests or reduce soil fertility in the long-term. Innovations in land-use management should not disrupt local systems of land tenure or marginalise the activities of segments of the population. If planners fail to balance all of these variables, their recommendations are unlikely to be accepted and their efforts are not likely to be successful. Results from this project are clearly inadequate to define an optimal strategy for windbreak deployment in the Sahel that will satisfy *all* of these requirements but, it is possible, on the basis of this study, to define a strategy for windbreak deployment that will minimise problems caused by competition between trees and crops for water.

The key to minimising competition for water in windbreak systems is to balance demand for water by the windbreak trees with the supply available from soil volumes outside those on which crops are dependent for their water. This has two important implications:

(1) At locations where windbreaks have access to groundwater or deep reserves of soil water, choice of tree species and strategies for canopy management are not crucial determinants of the effects of the windbreaks on crop productivity. At these locations, planners have a greater scope for using an array of tree species, so that the economic value of the windbreaks can be enhanced by using them to produce a broad range of goods needed by local people. Two notes of caution are required, however. First, the tree species used must have rooting habits that allow them to reach the groundwater. Second, the trees must not use so much water that groundwater levels at the site decline in the long-term, as this could result in wells running dry and would be disastrous for communities in the Sahel.

(2) At locations where groundwater or deep reserves of soil moisture 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 windbreaks at these locations must first choose tree species that demand small amounts of water. This selection should be made on the basis of knowledge of actual water use by species growing under relevant conditions or from relative leaf area densities and stomatal conductances typical for species under these conditions. Planners should select species with root systems that do not spread laterally for large distances in the top 2 m of the soil or recommend, where warranted by the returns on labour invested, pruning

of tree roots in the top of the soil profile. These decisions should be made on the basis of studies of the rooting habits of Sahelian trees. Finally, planners must decide how best to manage windbreak canopies once they are established. A major tool for reducing demand for water by windbreak trees at critical times of the year should be pruning of the canopy. Planners must decide on the timing and severity of pruning and the desired shape of the pruned canopy. Another important benefit of pruning schemes is that, in regions with relatively high annual rainfall, pruning may allow species to be used in windbreaks that would otherwise be considered unsuitable because of strong competitive effects on crops. This might permit, for example, use of species with high-value products rather than less competitive species with products of lower value.

## 7.5 Modelling water use by windbreaks

The confidence with which land-use planners are able to devise recommendations concerning the deployment of windbreaks in the Sahel could be improved if the effects of different tree species or management strategies on crop and tree productivity could be assessed quantitatively using a simulation model of tree and crop growth in windbreak systems. A process-based model of the ecological processes associated with windbreaks that can be applied to Sahelian farming systems should therefore be developed, preferably simulating water use by windbreak trees using procedures that can be parameterised using data collected in a survey of the canopy and root characteristics of trees adapted to the Sahel. Use of such a tool would permit agroforesters to test the productivity of various combinations of tree species, pruning schemes and cropping systems in a range of climatic and hydrological settings. Promising combinations of trees, crops and management approaches could be identified and then tested under real conditions in the field. The advantages of such an approach are that simulation runs are much cheaper than multi-year, multi-location field trials and that they take much less time, so that the delay between the inception of an idea and its recommendation to planners can be shortened. These are particularly important concerns in agroforestry because it can take many years to establish trials and transfer new technologies to farmers as trees take a long time to grow. Ultimately, it should be possible for land-use planners to use such a model to predict the effects of proposed windbreaks at specific sites. If models of alternative schemes for land-use management were also available, planners could make comparisons among a variety of options and generate specific hypotheses for testing in the field with local people.

A model of windbreak systems in the Sahel would necessarily include parallel simulations of both tree and crop growth. Data presented by Brenner (1991) should be utilised in the development of models of crop growth in the shelter of windbreaks in the Sahel and data collected during this project should be used to help develop, parameterise and validate procedures for calculating water use by windbreak trees. As discussed in Chapter 6, close coupling of windbreaks to the ambient atmosphere implies that transpiration by windbreaks depends mostly on the ambient vapour pressure deficit and the surface conductance of the canopy, so that simulation of water use by windbreak trees requires accurate estimates of surface conductances without the need for a detailed simulation of net radiation absorption by the canopy. Thus, further work is required to quantify the responses of stomatal conductances of trees in windbreaks to environmental conditions and to develop mathemetical descriptions of the phenology of leaf area development in a range of tree species suitable for use in windbreaks in the Sahel. Further quantitative research on root growth and the acquisition of soil water from different sources is also required before models of water uptake by windbreaks in the Sahel can be validated.

### 7.6 The role of windbreaks in agricultural development in the Sahel

A large majority of people in the Sahel live in rural areas and rely solely on the productivity of their land for sustenance and the materials used to provide shelter for themselves. The countries of the Sahel are not well-endowed with natural resources that can be exploited for their economic value and so the quality of life for the people of the Sahel is only likely to improve if land-use management can become more productive. Resources that could be used to boost crop yields or increase the diversity of crops grown in the Sahel are either not available or not affordable for farmers in the region and so it is important that land-use management becomes more efficient in the future, so that more food, fuel and fodder is produced from the available land, livestock and human labour. At present, this appears to be the only method by which sufficient food and wood can be produced to meet the increasing demands of a quickly growing population. Already, however, many parts of the Sahel are heavily reliant on food provided by external donors and climate change appears to be increasing constraints on agriculture. Thus, it seems unlikely that agriculture in the Sahel will be able to fulfil the requirements of the population in the future without increases in inputs and some degree of intensification. It is difficult to imagine from where the economic resources necessary to finance such intensification can be derived without further increasing the reliance of Sahelian countries on foreign aid.

If intensification of agriculture in the Sahel is unlikely to proceed because of lack of resources, it is imperative that the efficiency and sustainability of land use is increased. Recent decades have seen rapid degradation of areas of the Sahel as drought and deforestation have reduced the capacity of land to sustain local people. Loss of top soil by erosion has increased, so that there is an apparent downward spiral of resource depletion and resource loss at work that is increasing the vulnerability of people to environmental perturbations. This is not uniformly true across the Sahel, however, and so efforts must be made to conserve tree cover and soils at locations where degradation of the land is not well advanced. At such locations, the parkland system of agroforestry commonly continues to function and so researchers can aid agricultural development in these areas by investigating the role played by dispersed trees in soil conservation, nutrient cycling and the provision of tree products to livestock and people. When the processes underlying the inter-relationships between trees, crops and animals in the parkland system are understood, researchers, development agents and farmers can devise ways of increasing the efficiency with which desired products are produced by the system. Such research should also provide information that can help people avoid interventions in the parkland system that will ultimately cause the breakdown of the system and then degradation of the environment.

Where the parkland system has already broken down, windbreaks have a very important role to play. They can be used to arrest soil erosion where tree cover has been lost and so stabilise crop production and restore security of food supplies for local people. It is vital, however, that when windbreak plantings are planned at these locations, adequate attention is given to choosing the most suitable array of tree species for use in the windbreaks and to planning management strategies that will optimise the balance between resource utilisation by the trees and the crops. Many compromises must be made between conflicting ecological and economic considerations when planning windbreaks, but competition between trees and crops for water can be minimised by using the strategy for windbreak deployment developed from the research described in this thesis. Further research on other interactions between windbreaks and crops in the Sahel needs to be undertaken using the same approach, however, so that planners can utilise knowledge of the mechanisms controlling all interactions between windbreaks and crops, both positive and negative, when evaluating the advantages and disadvantages of using windbreaks at particular locations. This would help ensure that the benefits to local people and the environment of the labour and money invested in planting windbreaks are as high as possible.

### 7.7 Recommenations for future research

The conclusions drawn from this project have highlighted the need for further research in the following areas:

(1) A survey of typical leaf areas and stomatal conductances of a broad range of tree species suitable for use in windbreaks in the Sahel should be undertaken. The goal of the survey would be to rank species on the basis of surface conductances in order to infer the relative amounts of water demanded by each species. Measurements should be made in a range of soil water and climatic regimes, so that stomatal responses to environmental variables such as soil moisture content and vapour pressure deficit can be determined. Ideally, these measurements should be made on trees in windbreaks, but this is unlikely to be possible because windbreaks of a range of species are not usually found at any one location. Consideration should, therefore, also be given to collecting similar data from isolated trees, which are common in the Sahelian landscape, and should be coupled to the atmosphere in a similar way to trees in windbreaks.

(2) The rooting patterns of a range of Sahelian species should also be surveyed. Excavation is laborious, but it should be possible to characterise the rooting habits of tree species by combining stable isotope techniques with determinations of soil moisture profiles near trees (e.g. by using a neutron probe or time-domain reflectometry (TDR)). The goal of this research should be to ascertain which trees can utilise groundwater and which have lateral roots that extract water from shallow soil layers at large distances from the tree. Measurements should be made at locations with contrasting groundwater regimes in order to determine the responses of each species to the proximity of groundwater.

(3) Where windbreak trees have access to groundwater or other deep reserves of soil water, research is required to determine the extent to which surface layers of the soil must dry out before extraction of water by roots is shifted away from the surface towards deeper layers of the soil. If the surface must become very dry before uptake from deeper layers begins, then competition between trees and crops for water will not be reduced by as much as if uptake from deeper layers begins early in the drying

of the surface. Tracing of uptake by trees using stable isotopes should therefore be used to monitor changes in the source of water utilised by windbreaks as time advances after a heavy rainfall event. In combination with measurements of soil water potential in the soil profile, the water potential at which trees cease using water from the rooting zone of the crop could then be determined.

(4) Agronomic trials of windbreak pruning strategies should be undertaken in order to quantify the effects of pruning windbreaks on crop yields and on the productivity of windbreak trees. Treatments tested in these trials should include pruning at various times of the year and with varying degrees of severity. Changes in the surface conductance of windbreak canopies as a result of pruning and consequent changes in water use by the pruned trees should also be measured in order to determine whether changes in leaf water potential in response to pruning diminsh the effectiveness of pruning for controlling water use by the trees.

(5) Consideration should also be given to using pruning to test the influence of a variety of canopy shapes on the extent of the zone sheltered by windbreaks. The goal of these trials should be to define a canopy shape that minimises water use by the trees but maximises the size of the area sheltered by the windbreaks.

(6) Water use by windbreak trees should be included in a model of tree and crop productivity in windbreak systems. At a minimum, such a model should be able to simulate the effects of changes in canopy conductances of windbreaks on total water use and to simulate the extraction of water from the soil by the trees. In combination with simulations of crop growth behind the windbreak, the model could then be used to assess changes in the influence of windbreaks on crop productivity likely to result from using different tree species and pruning schemes.

(7) The research described in this project, and the recommendations for future research, should be expanded to include trees in agroforestry parklands in the Sahel. Isolated trees growing in farmers' fields are very common throughout the Sahel and research is required to determine how effectively they control wind erosion when spread throughout extensive areas. It is possible that when present in sufficient numbers, they can slow wind speeds at the soil surface as effectively as windbreaks, especially

when other cultural practices, such as crop residue management, are also implemented. Agroforestry parklands may be an important alternative to windbreaks in drier areas because they may extract less water per unit of land areas than large windbreaks. A programme of research should therefore be undertaken to determine the effects of parklands on wind erosion and to assess the competitiveness of isolated trees with nearby crops. Such research should enable parkland systems to be modelled in the same way as proposed for windbreaks, so that the effects of different management strategies can be assessed and compared to alternative land-use systems that use windbreaks.

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# Appendix A

## Validation of the Heat-Pulse Technique for Measuring Tree Transpiration

### A.1 Introduction

Transpiration by trees can be measured by determining the rate at which sap flows through woody stems if fluxes of sap can be assumed equal to rates of water loss from foliage. This assumption requires that the 2 to 5 % of water taken up by plants that is used in photosynthesis is neglected and that measurements are made over a period of time that is long enough for changes in storage of water in the stems to be negligible (Swanson, 1994). Two methods of measuring sap flow have been developed and both use heat as a tracer for sap movement. In the heat-pulse technique, sap flow is estimated from the velocity at which a short pulse of heat moves along the stem, while in the heat-balance method, sap flow is determined by solving the energy budget of a continuously heated section of stem for heat loss by convection in the moving sap stream. Instrumentation employing heat-balance principles has been developed for large trees by Cermak *et al.* (1976) and for smaller woody and herbaceous stems by Sakuratani (1981), Baker and van Bavel (1987) and Ishida *et al.* (1991). The heat-pulse technique is well suited to use in woody stems larger than 30 mm in diameter (Swanson, 1994) and has been shown to agree to within 5 to 10 % with transpiration rates determined using lysimetry when wood is thermally homogeneous and corrections are made for the influence of implanted probes on heat transfer (Swanson and Whitfield, 1981; Caspari *et al.*, 1993). The heat-pulse method was considered suitable for the range of tree sizes encountered in the studies of water use by trees in windbreaks described in this thesis, but to ensure that it provides accurate measurements of transpiration when used with the species studied, a series of experiments was done to validate the method and determine whether calibration of measurements is required in these species.

### A.2 Theoretical basis of the heat-pulse technique

The heat-pulse technique is based on the compensation principle whereby the movement of a pulse of heat by convection in the moving sap stream of a stem is determined by compensating the measured velocity of the heat-pulse for the dissipation of heat by

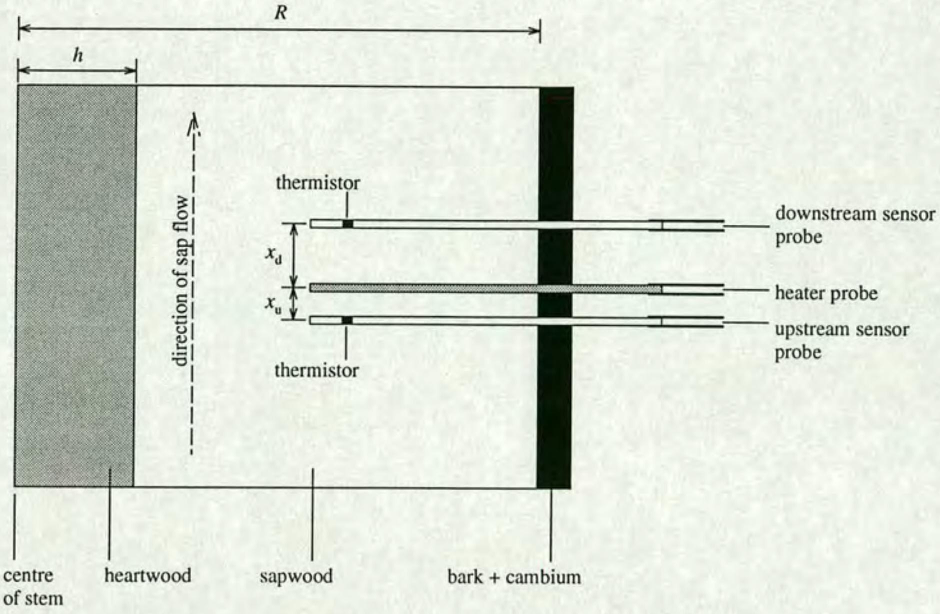

**Figure A.1:** Configuration of a single set of heat-pulse probes implanted radially into a stem of radius $R$ at the cambium and $h$ at the heartwood boundary. The upstream temperature sensor is installed at a distance $x_u$ below the heater and the downstream sensor is installed at a distance $x_d$ above the heater.

conduction through the matrix of wood fibres, water and gas that make up the stem (Swanson, 1994). In modern instruments, this is accomplished by deploying temperature sensors upstream and downstream of the heat source at unequal distances (Swanson and Whitfield, 1981). In these configurations, heat-pulses of 1 to 2 s duration are applied to stems using radially-implanted line heaters and the movement of the heat pulse is detected using an upstream sensor placed nearer to the heater than a downstream sensor (Fig. A.1). Immediately after the heat pulse is applied, the temperature of wood becomes greater at the closer, upstream sensor because of conduction, but heat carried by the moving sap then quickly warms the downstream sensor, so that the temperature of the two sensors is again equal after a time ($t_0$) in the order of 60 s. This is the time required for convection in the moving sap stream to move the peak of the heat pulse from the heater to the point midway between the two temperature sensors, so that $t_0$ decreases as sap velocity increases. The velocity of the heat pulse ($v_h$) is thus given by (Swanson and Whitfield, 1981)

$$v_h = \frac{0.5(x_u + x_d)}{t_0}, \tag{A.1}$$

where $x_u$ is the (negative) distance between the heater and the upstream temperature sensor and $x_d$ is the distance from the heater to the downstream sensor (Fig. A.1).

Marshall (1958) demonstrated analytically, however, that $v_h$ in woody stems is not the same as sap velocity. His analysis of the diffusion of heat in wood with moving sap showed that heat ascends the stem more slowly than sap because of the transfer of heat between the moving sap and the stationary, interstitial tissue between xylem vessels. For thermally homogeneous wood, where xylem vessels are uniformly spaced and interstitial thicknesses are sufficiently small that the time required for equilibration of sap and woody matrix is negligible, Marshall found that the velocity of sap in the xylem vessels ($v_s$) is related to $v_h$ by

$$av_s = \frac{\rho_{sm} c_{sm}}{\rho_s c_s} v_h \, , \tag{A.2}$$

where $a$ is the fraction of the cross-sectional area of conducting sapwood occupied by moving sap streams and $\rho$ and $c$ are density and specific heat capacity, with the subscripts s and sm refering to sap and sap plus woody matrix (including gas), respectively. The volumetric sap flux density per unit cross-sectional area of sapwood ($q_v$) is then given by

$$q_v = av_s \, , \tag{A.3}$$

so that, provided the condition of thermal homogeneity is satisfied, by combining Equations A.2 and A.3 it is theoretically possible to determine total sap flow rates for a tree stem from measurements of $v_h$ if $\rho_s$, $\rho_{sm}$, $c_s$, $c_{sm}$ and the cross-sectional area of sapwood are known.

Swanson and Whitfield (1981) used a numerical analysis of the dissipation of a heat pulse in wood to show, however, that before sap fluxes are calculated using Equation A.2, measured values of $v_h$ must be corrected to account for the influence on heat transfer of wounding to the tree caused by implantation of the heater and temperature sensors into the stem. This correction can be made using functions derived by Swanson and Whitfield (1981) and Green and Clothier (1988) for a variety of spacings and materials used to construct the heater and sensor probes.

Because sap velocities in woody stems normally vary with radial depth, sensors are usually implanted at several depths below the cambium of a stem, so that the radial profile of sap flux density across the sapwood can be determined. Mass flow rates of sap through the stem ($Q_m$) are then calculated from the integral of the sap flux profile over the cross-sectional area of the sapwood, which is (Green and Clothier, 1988; Green, 1993)

$$Q_m = \rho_s 2\pi \int_h^R r_d q_v'(r_d) \mathrm{d}r_d \, , \tag{A.4}$$

where $q_v'(r_d)$ is sap flux density calculated with corrected values of $v_h$ as a function of radial depth ($r_d$) in a stem of radius $R$ at the cambium and $h$ at the heartwood boundary. The function $q_v'(r_d)$ can be determined by fitting a second order least squares regression equation to the sap flux profile (Edwards and Warwick, 1984; Green and Clothier, 1988) or from a step function of sap flux density with depth (Hatton *et al.*, 1990). Where measurements are made on the trunk of a tree and where the assumption holds that the rate of sap flow and the rate of water loss from the foliage are equal, $Q_m$ is the transpiration rate of the tree.

Thus, for species with wood anatomy that can be considered thermally homogeneous, the heat-pulse technique can be used to measure transpiration without calibration. However, if the distribution of sap-conducting xylem vessels in the sapwood is markedly non-uniform or if the interstitial distances between vessels are too large for the time required for thermal equilibration between sap and woody matrix to be considered negligible, then transpiration rates calculated from measurements of heat-pulse velocity using Equations A.1 to A.4 are likely to be in error (Marshall, 1958; Swanson and Whitfield, 1981; Swanson, 1994). Swanson (1983) concluded that interstitial thicknesses of more than 0.4 mm are sufficient to cause thermal inhomogeneities. The technique consequently works well in softwood species (Swanson and Whitfield, 1981; Swanson, 1994) and in ring-porous or diffuse-porous hardwoods with closely-spaced xylem vessels (Green and Clothier, 1988; Swanson, 1994), but in other hardwoods, it may be necessary to rely on empirical calibrations in order for the heat-pulse technique to be used to measure transpiration accurately. The validity of the technique and the form of any required calibration functions can be determined by comparing transpiration rates estimated by the heat-pulse method with rates measured independently (Green and Clothier, 1988).

## A.3 Materials and methods

### **A.3.1** *Heat-pulse apparatus*

The procedures used to measure heat-pulse velocities in the studies described here and in other chapters were outlined by Edwards and Warwick (1984) and the apparatus employed was supplied by HortResearch of Palmerston North, New Zealand. Four sets of heat-pulse probes were used to make measurements on each stem studied, each consisting of one heater probe, constructed from constantan resistance wire in a teflon sleeve and a 1.8 mm o.d. stainless steel tube, and two thermistor probes constructed from 1.8 mm o.d. teflon tubes containing miniature thermistors. Each set of probes was installed in one of four sectors making up the circumference of the stem under study. The probes were implanted into parallel holes drilled radially into each stem using 1.80 or 1.85 mm-diameter drill bits, with the lower (upstream) thermistor probe installed 5 mm below the heater and the upper probe installed 10 mm above the heater. The pair of thermistors (≈1 mm in width) in each set of probes were installed so that they were located at a different depth in each sector between 5 mm below the cambium and the heartwood boundary. Sap velocities were thus sampled at four radial depths in the sapwood. The heater and thermistor probes were connected to a logger unit (Custom HP1) which controlled the pulsing of the heaters, monitored output from the thermistors, timed the passage of the heat pulse and logged the data for future analysis. In this approach, each pair of thermistors is connected in a Wheatstone bridge configuration, so that the logger records $t_0$ in Equation A.1 as the time taken after application of a heat pulse for the bridge to return through the balance point. In all of the studies described here, the duration of the heat pulse was 1 s.

Equations A.2 and A.4 show that in order to convert heat-pulse velocities to rates of sap flow, values of $\rho_s$, $\rho_{sm}$, $c_s$, $c_{sm}$, $h$ and $R$ are required. In the approach of Edwards and Warwick (1984), $\rho_s$ and $c_s$ are assumed to be the same as for water, while $\rho_{sm}$ and $c_{sm}$ are estimated by weighting the densities and heat capacities of sap and woody matrix by the volume fractions of each in fresh wood, assuming that the contribution of the gas content of the wood to each value is negligible. Values for the density ($1530\ \mathrm{kg\ m^{-3}}$) and heat capacity ($1380\ \mathrm{J\ kg^{-1}\ K^{-1}}$) of woody matrix are taken from the literature and are considered to be constant within and between species. The volume fractions of sap and woody matrix in the wood of each stem studied were determined by measuring the fresh mass, oven-dry mass and volume (as immersed mass, on the basis of Archimedes' principle) of samples taken from each stem using an increment borer. Values of $R$ and $h$ for each stem were determined by visually examining the same samples. Finally, the function $q'_v(r_d)$ in Equation A.4 was determined by fitting a second order least squares regression equation to the measured sap flux density profile, except where this caused extrapolation to unrealistically high sap fluxes at the cambium or heartwood boundary, in which case the step function approach described by Hatton *et al.* (1990) was used instead.

### **A.3.2** *Heat-pulse validation experiments*

Two methods were employed to test the heat-pulse technique in *Azadirachta indica* A. Juss., *Acacia holosericea* A. Cunn. ex G. Don and *Acacia nilotica* ssp. adstringens (Schumach. & Thonn.) Roberty, both based on experiments described by Green and Clothier (1988). The first method was undertaken in the laboratory at Edinburgh University and the second was carried out using excised branches at the ICRISAT Sahelian Centre (ISC), 45 km south of Niamey in Niger. Branches were cut from trees growing at ISC for use in both methods. Branches selected for use in the laboratory method had diameters of 5-7 cm and were cut into lengths of approximately 20-25 cm with a saw and frozen at -18°C until transported to Edinburgh where they were again frozen until used. The branches used in the excised-branch method were of similar girth and were cut immediately prior to use.

#### *Laboratory method*

Before use, each section of branch used in the laboratory method was thawed and trimmed to a length of 10-12 cm. Each end of the branch was then shaved using a sharp chisel, so that exposed xylem vessels on each cut face were not clogged by debris. The heat-pulse probes were implanted into the branch in the normal way at a position roughly half way along its length. Rubber o-ring gaskets were glued to each end of the branch, which was then clamped between two perspex plates connected to Tygon tubing, so that the gaskets formed seals between the cut face and the perspex at each end of the branch (Fig. A.2).

Distilled, de-aerated and filtered (0.1 μm) water was forced through each branch tested by raising the source reservoir above the outlet of the tubing. Before measurements were made, the branch was saturated by allowing water to flow through it for 10 to 15 min. The outlet of the tubing was then arranged so that water flowed into a flask on the weighing pan of a sensitive electronic balance. The mass of the flask was logged every 1 s on a computer and the data used to calculate the actual rate of flow of water through the branch. Flow rates were measured simultaneously by the heat-pulse method and logged on a heat-pulse logger. Flow rates were varied by altering the height of the source reservoir and four measurements were made at each flow rate. At the conclusion of each set of measurements,

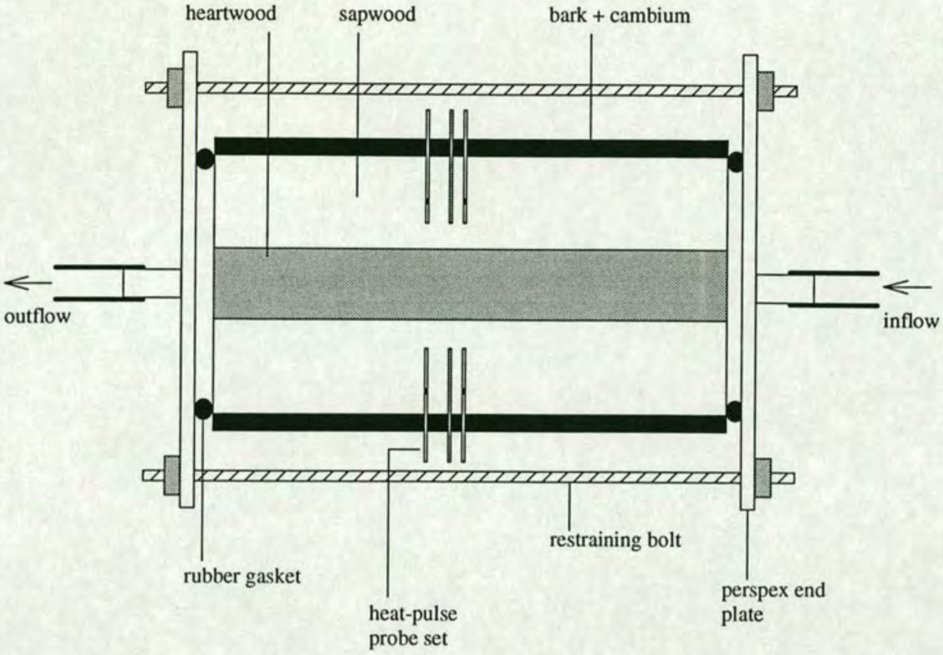

**Figure A.2:** Cross-sectional view of the apparatus used in the laboratory to test the heat-pulse technique in a segment of stem. Two of the four sets of heat-pulse probes are shown; the remaining two were installed perpendicular to the cross-section.

toluidene blue (1% m./v.) was passed through the branch in order to highlight wood through which conduction actually occurred and allow the effective sapwood area to be determined accurately. Samples of the branch were taken with an increment borer and used to determine the volume fractions of water and woody matrix. Measurements were made on at least two branches of each species.

*Excised-branch method*

The excised-branch method tested the performance of the heat-pulse technique in whole branches under field conditions. It was used with *Azadirachta indica* and *Acacia holosericea* but not *Acacia nilotica*. Heat-pulse probes were installed in each selected branch before it was cut from the tree with a saw and re-cut under water approximately 15 cm above the first cutting point. Following, re-cutting, the base of the branch was kept submerged at all times in order to prevent embolism of the xylem vessels open at the cut face. A sharp chisel was used to shave the cut end and the branch was then mounted in a drum containing clean tap water.

The branch and drum were suspended from a 250 kg-capacity load cell (RS Components, Corby, UK.) attached to a steel tripod and the top of the drum was sealed with plastic to prevent loss of water by evaporation. Actual transpiration from the branch was calculated from the rate of change in the weight of the suspended drum and branch, which was measured using the load cell and recorded at 60 s intervals using a data logger (21X, Campbell Scientific Ltd., Shepshed, UK.). Sap flow through the branch was simultaneously measured using the heat-pulse method and recorded every 15 min using a heat-pulse logger. Measurements were made continuously for several hours until transpiration from the branch had diminished to a low rate. The apparatus was erected inside a greenhouse in order to reduce variability in the measurements of branch mass resulting from gusts of wind. Toluidene blue was again used after each set of measurements to mark the zone of active conduction through the branch and samples of wood were collected and used to determine the volume fractions of water and woody matrix.

### A.3.3 *Data analysis*

Flow rates measured using the heat-pulse method were plotted against actual flow rates and factors for correcting rates of sap flow estimated by the heat-pulse technique were calculated using linear regression.

## A.4 Results and discussion

Data from both the laboratory and field trials show that the heat-pulse technique seriously underestimates true flow rates in all three species (Fig. A.3). Data from the field trials for *Azadirachta indica* and *Acacia holosericea* generally support the results from the laboratory study, but are more variable, probably because measurements of the change in mass of the apparatus used in the field trial were not sufficiently precise. Calibration factors for correcting flow rates measured using the heat-pulse method were consequently determined on the basis of the results from the laboratory trials only. The calibration functions for each species are given in Table A.1. Brenner (1991) used the laboratory method on *Azadirachta indica* branches and found a similar result, but he chose to correct for the

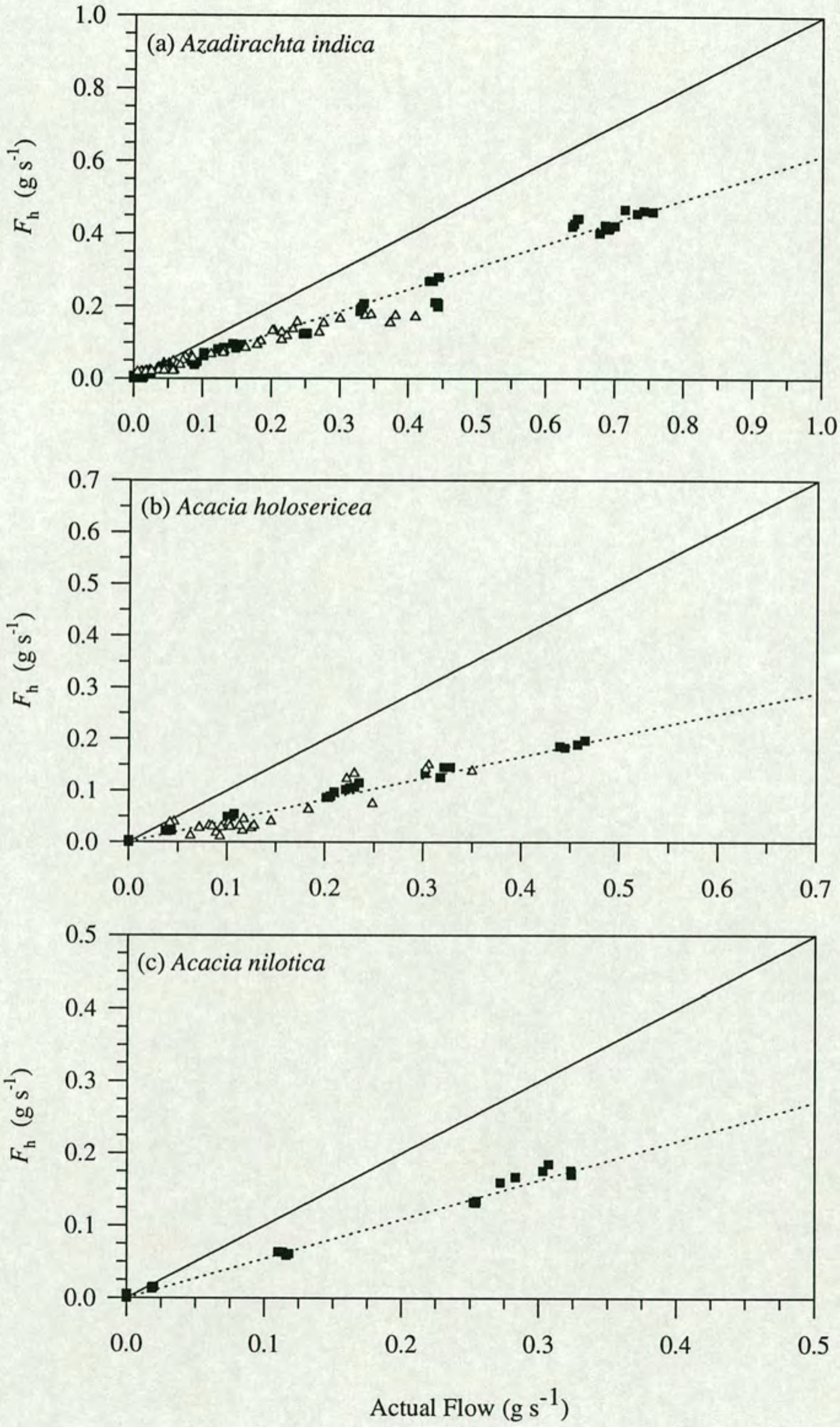

**Figure A.3:** Comparisons between flow rates measured using the heat-pulse technique ($F_h$) and actual flow rates measured with the laboratory (■) and field (△) methods in branches of (a) *Azadirachta indica*, (b) *Acacia holosericea* and (c) *Acacia nilotica*. Results from the laboratory method are from two branches per species. The solid lines are 1:1 and the dotted lines are fitted calibration functions (Table A.1).

**Table A.1:** Calibration equations used to calculate corrected sap flow rates ($F_c$) from sap flow measured using the heat-pulse method ($F_h$).

| Species | Heat-Pulse Calibration Equation | $r^2$ | Eq. No. |
|---|---|---|---|
| *Azadirachta indica* | $F_c = 1.620F_h$ | 0.98 | (A.5) |
| *Acacia holosericea* | $F_c = 2.425F_h$ | 0.99 | (A.6) |
| *Acacia nilotica* | $F_c = 1.847F_h$ | 0.99 | (A.7) |

underestimation of flow rates by increasing the size of the implantation wound, which then altered the values of the coefficients in the functions developed by Swanson and Whitfield (1981) to correct heat-pulse velocities for the effects of wounding of the stem.

Green and Clothier (1988) found similar results for kiwifruit (*Actinidia deliciosa* (Chev.) C.F. Liang & A.R. Ferguson) stems using the same techniques, while the heat-pulse method proved to measure transpiration rates in apple trees (*Malus sylvestris* Mill.) accurately. They concluded that the disparity between the two species was caused by differences in wood anatomy because the apple stems studied had small, closely-spaced xylem vessels while the kiwifruit wood contained large-diameter xylem vessels with interstitial distances of 0.1 to 0.8 mm. Thus, the condition of thermal homogeneity required for accurate measurements of sap flow using the heat-pulse theory summarised by Equations A.1 to A.4 was not met by the kiwifruit wood and errors in measurement occurred.

Examination of sections of wood from *Azadirachta indica*, *Acacia holosericea* and *Acacia nilotica* showed that the underestimation of rates of sap flow in these species probably resulted from the same cause. Mean distances between randomly selected, neighbouring xylem vessels measured under a microscope are given in Table A.2 for each species. In each case, mean interstitial distances between xylem vessels were close to or more than the threshold value of 0.4 mm that Swanson (1983) found was sufficient to cause thermal inhomogeneities in wood. Thus, the underestimation of flow rates by the heat-pulse method in all three species likely resulted from thermal inhomogeneities in the wood of each species caused by large interstitial thicknesses between xylem vessels.

## A.5 Conclusions

Transpiration rates in trees of *Azadirachta indica*, *Acacia holosericea* and *Acacia nilotica* measured using the heat-pulse technique must be corrected using the equations

**Table A.2**: The mean distance between neighbouring xylem vessels ($\overline{d_v}$) in sapwood of *Azadiracta indica*, *Acacia holosericea* and *Acacia nilotica*.

| Species | $\overline{d_v}$ (mm) | ±s.e. |
|---|---|---|
| *Azadirachta indica* | 0.43 | 0.07 |
| *Acacia holosericea* | 0.38 | 0.06 |
| *Acacia nilotica* | 0.46 | 0.08 |

listed in Table A.1. This finding emphasises the importance of the conclusion discussed by Swanson (1994) that when applying the heat-pulse method to tree species for which the method has not been validated, investigators must be aware of the potential for errors to arise as a result of the characteristics of the sap conducting system in each species.

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# Appendix B

## Allometric Relationships Used to Estimate Leaf Area in 1991

### B.1 Introduction

Leaf areas of windbreak trees on which transpiration was measured in 1991 using the heat-pulse technique (Chapter 2) were not determined directly by removing all leaves from each tree studied and measuring the area of leaves harvested, as was done in 1992 and 1993. Instead, leaf areas of branches in which the heat-pulse apparatus was implanted were estimated from allometric relationships between leaf area and the cross-sectional area of branches. These relationships were developed from measurements of the area of leaves on branches of other trees of *Azadirachta indica*, *Acacia holosericea* and *Acacia nilotica* growing in the hedge windbreaks at the Sadoré location where the measurements of transpiration were made.

### B.2 Methods

All leaves were harvested from 40 branches of *Acacia holosericea* on DOY 259, 1991 and from 40 branches of *Azadirachta indica* on DOY 260, 1991. The projected leaf area ($A_{lb}$) for each branch was then measured by passing each leaf collected through a leaf area meter (LI-3100, Li-Cor Inc., Lincoln NE, USA). For *Acacia nilotica*, leaves were harvested from only 20 branches because the sharp thorns of this species made the collection of leaves very difficult. The leaves were harvested on DOY 261, 1991, and leaf areas for each branch were estimated as the product of the dry mass of the leaves and specific leaf area. Values of specific leaf area were determined from the leaf area of a subsample of a few leaves from each branch which had been placed between the pages of a book immediately after collection in order to prevent the leaflets from folding up. The leaf area of each subsample of *Acacia nilotica* leaves was measured by passing the leaves through the leaf area meter.

Basal diameters of these branches were measured with calipers when the leaves were harvested and ranged between 0.3 and 5.0 cm. The cross-sectional area of each

**Table B.1:** Linear regression equations relating leaf area ($A_{\mathrm{lb}}$) to basal cross-sectional area ($A_{\mathrm{bx}}$) for branches of *Azadirachta indica*, *Acacia holosericea* and *Acacia nilotica* at Sadoré in 1991.

| Species | Equation | $r^2$ | Eq. no. |
|---|---|---|---|
| *Azadirachta indica* | $\ln A_{\mathrm{lb}} = 8.09+1.05(\ln A_{\mathrm{bx}})$ | 0.95 | B.1 |
| *Acacia holosericea* | $\ln A_{\mathrm{lb}} = 7.73+1.15(\ln A_{\mathrm{bx}})$ | 0.93 | B.2 |
| *Acacia nilotica* | $\ln A_{\mathrm{lb}} = 7.62+1.45(\ln A_{\mathrm{bx}})$ | 0.94 | B.3 |

branch ($A_{\mathrm{bx}}$) was estimated from the branch diameter by assuming that the cross section of each branch was circular.

### B.3 Results

Values of variance for leaf area were proportional to the magnitude of $A_{\mathrm{lb}}$, but as shown in Fig. B.1, a close linear relationship existed between the logarithms of $A_{\mathrm{lb}}$ and $A_{\mathrm{bx}}$ for each species. Equations fitted to the data for each species by linear regression are given in Table B.1.

In order to use these equations to estimate the projected leaf area ($A_{\mathrm{l}}$) of each branch on which measurements of transpiration were made in 1991, determinations were made of the cross-sectional areas of branches leaving the branch into which the heat-pulse probes were implanted. This was done so that all leaves present in each case were connected to only one measured branch. The leaf area for each measured branch was then estimated using the appropriate equation in Table B.1 and $A_{\mathrm{l}}$ estimated by summing together the estimated leaf areas ($\hat{A}_{\mathrm{lb}i}$)for all $i$ branches out of the total $n$ using:

$$A_{\mathrm{l}} = \sum_{i=1}^{n} \hat{A}_{\mathrm{lb}i} \,. \tag{B.4}$$

This procedure was repeated each time the heat-pulse probes were installed and the values of $A_{\mathrm{l}}$ determined were used in the calculation of rates of tranpiration per unit leaf area, as discussed in Chapter 2.

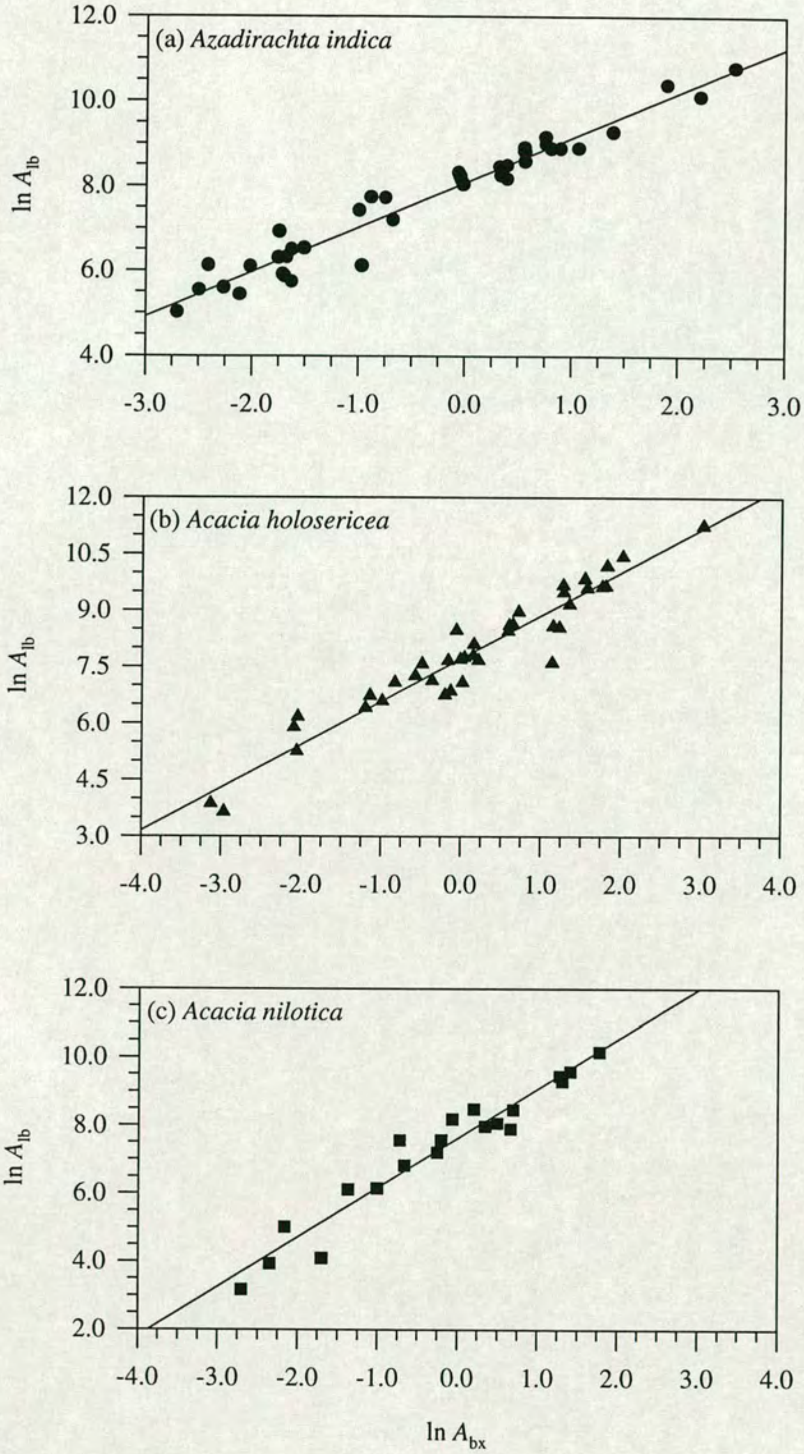

**Figure B.1:** The relationships between the logarithms of leaf area ($A_{lb}$) and basal cross-sectional area ($A_{bx}$) for branches of (a) *Azadirachta indica*, (b) *Acacia holosericea* and (c) *Acacia nilotica* at Sadoré in 1991. Equations for the fitted lines are given in Table B.1.

# Appendix D

## Symbols Used in the Text

**Latin alphabet:**

| | |
|---|---|
| $A$ | available energy ($R_n$-$\Delta S$) |
| $A_{bx}$ | cross-sectional area of a branch |
| $A_c$ | projected crown area of a tree |
| $A_i$ | projected leaf area of the instrumented tree enclosed by the net radiometer array |
| $A_l$ | projected leaf area |
| $A_{lb}$ | projected leaf area of a branch |
| $\hat{A}_{lb}$ | estimated leaf area of a branch |
| $A_{lj}$ | projected leaf area of layer $j$ of a tree crown |
| $A_r$ | projected area of a leaf replica |
| $A_t$ | total projected leaf area of a tree crown |
| $b$ | coefficient in generalised equation for leaf boundary layer conductance |
| $c$ | intercept term in Equation 2.9 (Chapter 2);<br>intercept term in generalised equation for leaf boundary layer conductance (Chapter 4) |
| $c_p$ | specific heat capacity of air at constant pressure |
| $c_s$ | specific heat capacity of plant sap |
| $c_{sm}$ | specific heat capacity of sap plus woody matrix (moist wood) |
| $d$ | characteristic dimension of a leaf or leaf model |
| $d_i$ | thickness of soil layer $i$ |
| $\overline{d}_v$ | mean distance between xylem vessels |
| $d_y$ | day of the year |
| $D_a$ | ambient vapour pressure deficit |
| $D_{eq}$ | equilibrium vapour pressure deficit |
| $D_{max}$ | daily maximum vapour pressure deficit |
| $D_s$ | vapour pressure deficit at the surface |
| $\mathrm{e}^*$ | saturation vapour pressure |
| $e_a$ | ambient vapour pressure |
| $e_{cs}$ | vapour pressure at the surface of a windbreak canopy |
| $E$ | evapotranspiration rate or transpiration rate |
| $E_{eq}$ | equilibrium transpiration rate |
| $E_{ht}$ | evaporation rate from the saturated crown of an excised tree ("hanging tree") |
| $E_{imp}$ | imposed transpiration rate |
| $E_t$ | transpiration rate for a single tree |

| | |
|---|---|
| $f_{\mathrm{l}}$ | ratio of the leaf areas of Tree HT1 and Tree S93 (Chapter 4) |
| $f_{\mathrm{tw}}$ | scaling factor for converting transpiration per tree to transpiration per unit of windbreak length |
| $F_{\mathrm{c}}$ | corrected sap flow rates |
| $F_{\mathrm{h}}$ | sap flow rates measured by the heat pulse method |
| $g_{\mathrm{a}}$ | bulk aerodynamic conductance for a tree crown |
| $g_{\mathrm{ac}}$ | aerodynamic conductance for transfer between the limits of leaf boundary layers and the air at reference height |
| $g_{\mathrm{aH}}$ | bulk aerodynamic conductance for heat transfer for a tree crown |
| $g_{\mathrm{aV}}$ | bulk aerodynamic conductance for vapour transfer for a tree crown |
| $g_{\mathrm{aw}}$ | bulk aerodynamic conductance for a windbreak canopy |
| $g_{\mathrm{b}}$ | leaf boundary layer conductance |
| $g_{\mathrm{b}}'$ | boundary layer conductance for one side of a smooth flat plate |
| $g_{\mathrm{bt}}$ | summed leaf boundary layer conductance for a tree crown |
| $g_{\mathrm{c}}$ | surface conductance of a plant canopy |
| $g_{\mathrm{cw}}$ | surface conductance for a windbreak canopy |
| $g_{\mathrm{cw}}^{\mathrm{max}}$ | daily maximum $g_{\mathrm{cw}}$ |
| $g_{\mathrm{s}}$ | stomatal conductance |
| $\hat{g}_{\mathrm{s}}$ | stomatal conductance estimated from the slope term of Equation 2.8 |
| $\overline{g_{\mathrm{s}}^{\mathrm{max}}}$ | daily maximum mean stomatal conductance |
| $g_{\mathrm{V}}$ | conductance for vapour transfer for a tree crown |
| $h$ | radius of the heartwood |
| $H$ | sensible heat flux |
| $i$ | increment variable |
| $I_{\mathrm{i}}$ | current input to leaf replica curcuit |
| $j$ | increment variable |
| $l_{\mathrm{i}}$ | length of the vertical section at the centre of the instrumented tree |
| $l_{\mathrm{t}}$ | length of the crown of the instrumented tree along the axis parallel to the windbreak |
| $L$ | leaf area index |
| $L_{\mathrm{w}}$ | linear leaf area density for a windbreak (ie. projected leaf area per unit length of windbreak) |
| $L_{\mathrm{w,i}}$ | linear leaf area density of the instrumented tree within the net radiometer array |
| $L_{\mathrm{w,n}}$ | linear leaf area density of neighbouring trees within the net radiometer array |
| $m_{\mathrm{t}}$ | fresh mass of a tree |
| $n$ | maximum value of *i* or *j;*<br>number of days (Chapter 5) |
| $n_{\mathrm{t}}$ | number of trees per unit length of windbreak |
| $P_{\mathrm{i}}$ | electrical power supply to a heated leaf replica |
| $P_{\mathrm{s}}$ | proportion of water taken up from a source *s* |
| $q_{\mathrm{v}}$ | volumetric sap flux density |
| $q_{\mathrm{v}}'$ | volumetric sap flux density from sap velocities corrected for wounding |

| | |
|---|---|
| $Q_m$ | mass flow rate of sap |

| | |
|---|---|
| $r_c$ | radius of notional cylinder around net radiometer array |
| $r_d$ | radial depth below the cambium |
| $R$ | radius at the cambium |
| $R_n$ | net radiation |
| $\overline{R_n}$ | mean net radiation measured around the net radiometer array |
| $R_{nc}$ | net radiation over a crop |
| $R_{nH}$ | net radiation absorbed by a heated leaf replica |
| $R_{nU}$ | net radiation absorbed by an unheated leaf replica |
| $R_s$ | solar radiation |
| $R_S$ | $^{18}O/^{16}O$ ratio for a sample |
| $R_{SMOW}$ | $^{18}O/^{16}O$ ratio for a Standard Mean Ocean Water |

| | |
|---|---|
| $s$ | slope of the saturation vapour pressure curve at the surface temperature |
| $S$ | heat storage in a windbreak canopy |

| | |
|---|---|
| $t$ | time |
| $t_0$ | heat pulse transit time |
| $T_a$ | ambient temperature |
| $T_l$ | leaf temperature |
| $T_s$ | surface temperature |
| $T_{sH}$ | surface temperature of a heated leaf replica |
| $T_{\underline{sU}}$ | surface temperature of an unheated leaf replica |
| $T_{wb}$ | wet bulb temperature |

| | |
|---|---|
| $u$ | wind speed |

| | |
|---|---|
| $v_h$ | heat pulse velocity |
| $v_s$ | sap velocity |
| Vi | voltage across leaf replica circuit |

| | |
|---|---|
| $x_d$ | downstream distance between heater and heat pulse temperature sensor |
| $x_u$ | upstream distance between heater and heat pulse temperature sensor |
| $X$ | exchange flux |

| | |
|---|---|
| $z$ | exponent in generalised equation for leaf boundary layer conductance |

**Greek alphabet:**

| | |
|---|---|
| $\alpha$ | $g_b(\Theta)/g_b(\Theta=0)$ (Chapter 4);<br>Priestley and Taylor coefficient (Chapter 5) |
| $\alpha_1$ | |
| $\alpha_2$ | regression coefficients for Equation 2.11 |

| | |
|---|---|
| $\beta$ | enhancement factor for boundary layer conductances above theoretical values (Chapter 4);<br>Bowen ratio (Chapter 5) |

| | |
|---|---|
| $\beta_1$ | |

| | |
|---|---|
| $\beta_2$ | regression coefficients for Equations 2.12a, 2.12b and 2.12c |
| $\beta_3$ | |
| $\beta_4$ | |
| $\gamma$ | psychrometric constant |
| $\delta_p$ | $\delta^{18}O$ value for plant sap |
| $\delta_s$ | $\delta^{18}O$ for water from a source *s* |
| $\delta^{18}O$ | $^{18}O/^{16}O$ ratio normalised to Standard Mean Ocean Water |
| $\delta^{18}O_i$ | $\delta^{18}O$ value for soil layer *i* |
| $\overline{\delta^{18}O}$ | mean $\delta^{18}O$ value for water in the soil profile or a portion of the soil profile |
| $\Delta$ | difference, or change over time |
| $\Delta\delta_l$ | difference in $\delta^{18}O$ values for water from two levels in the soil profile |
| $\varepsilon$ | $s/\gamma$ |
| $\theta_g$ | gravimetric soil moisture content |
| $\theta_v$ | volumetric soil moisture content |
| $\Theta$ | angle of inclination of a leaf replica |
| $\kappa$ | thermal diffusivity of air |
| $\lambda$ | latent heat of vaporisation |
| $\nu$ | composite variable defined by Eqution 2.10 |
| $\rho_a$ | density of dry air |
| $\rho_s$ | density of sap |
| $\rho_{sm}$ | density of sap plus woody matrix |
| $\rho_w$ | density of water |
| $\upsilon$ | kinematic viscosity of air |
| $\Omega$ | decoupling coefficient |

**Non-dimensional groups:**

| | |
|---|---|
| Nu | Nusselt number |
| Pr | Prandtl number |
| Re | Reynolds number |