Tree - Crop Interactions within a Sahelian Windbreak System

by

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of Philosophy to the University of Edinburgh 1991.

DECLARATION

I certify that this thesis has been composed by myself from the results of my work, except where stated otherwise, and has not been submitted in any previous application for a degree.

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ABSTRACT

The advantages of windbreaks in terms of reducing soil erosion and providing tree products for farmers in the Sahel are well known. There is less certainty about the effect of shelter on crop growth, the degree of competition for water and light between windbreak and crop, and almost no information on the amount of water a windbreak transpires over a year.

Field measurements of millet (*Pennisetum typhoides*) growth and microclimate behind a young double row neem (*Azardirachta indica*) windbreak at the ICRISAT Sahelian Centre, Sadoré, Niger, were carried out in 1988 and 1989. Measurements of tree transpiration were made using a commercial sap flow meter, along with measurements of tree heights, stem basal areas and leaf areas.

The reduction in wind speed produced by the windbreak changed over the season, as a result of the reduction of the porosity of the lower half of the windbreak by the growth of the millet crop on the windward side of the windbreak. Maximum shelter was found at 6*h* at the beginning of the cropping season and 3*h* during the middle and end of the season, where *h* is the height of the windbreak. Factors influencing the magnitude of shelter are discussed.

Shelter increased both air temperature and water vapour pressure. At the start of the season millet growth and development was delayed by shelter. However, as the season progressed shelter caused a more favourable climate for crop growth. It is suggested that crop response to shelter occurs because of (i) increased plant temperatures increasing rate of plant development and, (ii) a decrease in the vapour pressure deficit at the leaf surface which increases stomatal conductance and the solar radiation conversion ratio.

Leaf area of the neem was linearly related to stem basal area. So windbreak water use was estimated by normalizing tree transpiration to stem basal area and multiplying by the average stem basal area per unit length of windbreak. Transpiration rates of trees decreased as the dry season progressed.

Yield reductions as a result of windbreak-crop competition did not occur at distances exceeding 1.5*h* from the windbreak during the two years of trials. Below-ground competition and above-ground competition influenced biomass yields to a similar extent. Grain yield reduction by above-ground competition could not be attributed solely to a reduction in PAR. Optimum windbreak spacing based on 1989 results was calculated as 10 - 15*h*, which would provide grain yields that compensated for land area taken out of production and increased stover by 25 %.

The relative transpiration rates of the windbreak and crop were investigated. Averaged over the season the windbreak used up more water per unit land area than the millet. If the windbreaks were spaced 100 m apart a windbreak would use up 60 mm more water per year than would be used by a millet crop and bare soil, approximately 11 % of the annual rainfall.

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CHAPTER 1

INTRODUCTION AND SITE CHARACTERISTICS

1.1 BACKGROUND

The Sahel is characterized by strongly seasonal and unreliable rainfall, that has made drought a feature of the climate for centuries. The possibility of drought leading to famine has increased as traditional safety nets such as natural forest, and wild animals have become scarce. The progressive decline in *per capita* food production in the Sahel over the last 20 years has recently led to widespread famine. Poor crop yields have resulted from drought, low soil fertility and lack of efficient soil-water management (Youdeowei, 1987). Land degradation resulting from overgrazing, and reduction of the period that land is left to fallow, has increased both wind and water erosion, aggravating the cycle of poverty (Arnborg, 1988).

Clearing of forest land for agricultural production increases the scarcity of tree products and dry season fodder for livestock (Anderson, 1987). This has led to collection of firewood from the laterite plateaus, and has increased runoff and erosion on hill sides and flooding in valley bottoms (Coulter, 1989).

1.2 AGROFORESTRY

Agroforestry is a system of trees and crops and has been defined as;

> *'all land-use systems and practices in which woody perennials are deliberately grown on the same land management unit as crops and/or animals.'* (ICRAF, 1983)

Agroforestry has been seen as a possible solution to combining the need to increase agricultural production and reduce deforestation in the Sahel (Von Maydell, 1987). Most previous agricultural development has involved removing trees from agricultural land, but traditional agroforestry practices in both humid and semi-arid tropical zones are both productive and sustainable (MacDicken and Vergara, 1990). Many agroforestry systems exist in the Sahel (Von Maydell, 1987; Van Den Beldt, 1990) of which the *Faidherbia albida* parkland system is perhaps the best known. This system requires little management, no planting and has shown increases in annual crop yields under the tree canopy, as a result of reducing soil temperatures and increasing soil fertility (Dancette and Poulain, 1969).

Agroforestry systems (such as alley cropping) have been shown to increase maize yields in humid zones (Kang *et al.*, 1985), but have been less successful in semi-arid zones (Corlett, 1989; Ong *et al.*, 1991a). Long-term benefits of trees, in terms of tree products, reduction of erosion and increase of soil fertility are known (Ticknor, 1988; Young, 1989), but many farmers cannot afford short-term reductions in annual grain yield caused by a reduction in area of cropped land. Windbreaks as well as reducing soil erosion have been reported to increase crop production in their lee to an extent that compensates for land occupied by the trees (Jensen, 1954; Caborn, 1957; Van Eimern *et al.*, 1964; Grace, 1977; Sturrock, 1984; Kort, 1988). Thus there may be economic and ecological benefits of introducing windbreak systems in the semi-arid tropics.

1.3 WINDBREAKS

The introduction of a windbreak into a farmer's field causes a series of changes to the farming system.

1.3.1 Crop yields

Crop yields may increase (Van Eimern *et al.*, 1964; Kort, 1988), or decrease (Shah, 1961; Carr, 1985) in shelter. The magnitude and direction of change has been found in field trials to vary with windbreak design, species, degree of tree-crop competition, climate and sensitivity of crop to physical damage and changes in microclimate. Many reasons for yield increases in shelter have been suggested, one of the main ones being water conservation (Van Eimern *et al.*, 1964; Rosenberg *et al.*, 1983; Baer, 1989). This has led to suggestions that advantages of shelter would be larger in dry years and arid climates. The findings of Frank *et al.* (1974; 1977) contradicts these suggestions by showing that when water was restricted shelter decreased growth, whereas when water was available shelter increased growth, discussed in more detail in Section 2.1. Some understanding of this conflict can be gained by considering the wind pattern behind a windbreak.

1.3.2 Wind pattern

Change in horizontal wind speed and turbulence caused by a windbreak may affect plants by (i) physical damage and (ii) changing the energy balance with consequences for transpiration and water use.

1.3.2.1 Physical damage

Physical damage as a result of wind reduces fruit and vegetable quality (Baldwin, 1988; Norton, 1988), uproots seedlings at the beginning of the season and causes lodging of cereals (Sturrock, 1984). Short duration high speed winds or catastrophic storm events also cause soil erosion and sand blasting of leaves increasing cuticular conductance (Armbrust, 1984; Pitcairn and Grace, 1985), damaging tissues and even causing complete crop failure. Plants may change their form and growth rate in response to physical movement, the so-called 'thigmomorphogenesis' that has been shown to vary between species (Jaffe, 1973). Chemical composition of plants may also change in shelter, eg. higher crude protein (Younie and Ruxton, 1977), more digestible pasture (Sturrock, 1984) and sweeter sugar beet (Baldwin, 1988).

1.3.2.2 The leaf energy balance

The energy balance of a leaf may be written as;

$$R_{\mathrm{n}}^{\mathrm{a}} + \lambda E + H + S + G_{\mathrm{p}} + P_{\mathrm{s}} = 0, \qquad (1.1)$$

where $R_{\mathrm{n}}^{\mathrm{a}}$ is net radiation absorbed by the leaf, λE is latent heat flux (ie. transpiration), H is sensible heat flux, S is flux of heat energy into or out of leaf storage, G_{p} is flux of energy to the leaf by conduction, and P_{s} is energy used in photosynthesis. In practice S, and G_{p} in leaves are negligible, and P_{s} is rarely more than a few percent of $R_{\mathrm{n}}^{\mathrm{a}}$ (Monteith and Unsworth, 1990). So eq. 1.1 can be simplified to:

$$R_{\mathrm{n}}^{\mathrm{a}} = \lambda E + H \qquad (1.2a)$$

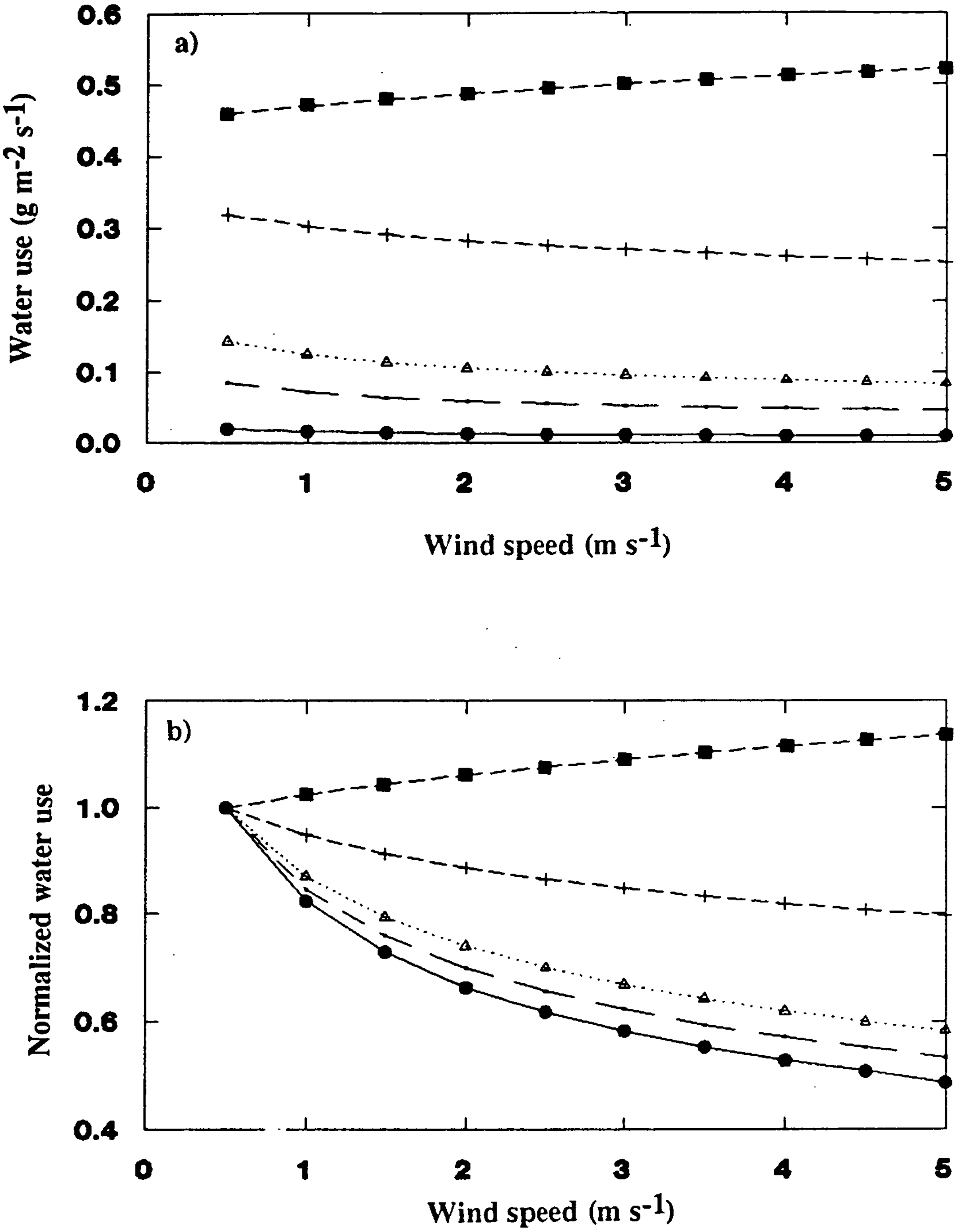


Figure 1.1 a) Change of water use from leaves with wind speed at different stomatal conductances. b) Change of water use from leaves normalized to water use at wind speed = 0.5 m s^{-1} with wind speed at different stomatal conductances. $g_s = \infty$ (■), g_s = 1.95 cm s^{-1} (+), g_s = 0.39 cm s^{-1} (△), g_s = 0.20 cm s^{-1} (·), g_s = 0.04 cm s^{-1} (●). $R_n{}^a$ = 450 W m^{-2}, D_a = 4 kPa, and T_a = 35 ^oC.

H, and reduces leaf-air water vapour pressure difference which reduces the transpiration rate (Figure 1.1a). The importance of this effect increases as g_s decreases (Figure 1.1b), and as T_a increases, because, for the same unit change in temperature the change in vapour pressure increases as T_a increases, as a result of the non-linear nature of the saturated water vapour pressure vs. temperature response curve (Monteith and Unsworth, 1990). If $g_s = \infty$ (wet canopy), water loss increases with wind speed. This suggests that if a windbreak affects g_a only then transpiration increases in shelter under arid conditions contrary to popular opinion (Grace, 1977;1988). However, evaporation of surface water would decrease in shelter, this is discussed further in Section 5.1.

1.3.3 Windbreak/crop competition

Trees compete with crops in a windbreak system for light, water and nutrients (Bates, 1911). Reductions in crop yield extend on average 0.5*h* to 2*h* into the field, where *h* is height of windbreak (Bates, 1911; Kort, 1988). The degree of competition depends on (i) quantity of resources used by the windbreak and (ii) amount of resources available. Growth resource requirements increase with size of canopy, and competition for these resources increases as resource availability decreases. So as water availability decreases, competition between windbreak and crop would be expected to increase, reducing yields adjacent to the windbreak. This is discussed further in Section 7.1.

1.3.4 Tree water use

Windbreaks transpire throughout the year, unless they drop their leaves, and so may transpire more than the millet they replace during the cropping season and certainly more than the bare soil they replace during the dry season. Little information is available on the water use of windbreaks in semi-arid areas, even though they may constitute a major component of the catchment water balance. Windbreak water use could be especially important where a windbreak has rooted into a water table (eg. the Maggia valley project in Niger, Dennison *et al.*, 1988; Kerkoff, 1991). Management of water resources in semi-arid areas requires a knowledge of windbreak water use if windbreak systems are to be planted and maintained in a sustainable way.

1.3.5 Products

Windbreaks can be used to produce firewood, fodder, fruit, building materials, and medicine. Such products may well be the most important aspect of windbreak planting for the farmer, as is now being demonstrated in the Maggia valley in central Niger (Kerkoff, 1991). These benefits are well known, and selection of the appropriate tree species should be based on the products desired, and site conditions.

1.3.6 Soil conservation and fertility

Most fertility is contained in easily erodable fine particles near the soil surface, so windbreaks increase fertility by reducing soil surface erosion and increasing soil organic matter (Ticknor, 1988). Improvements in soil fertility have been found under both leguminous and non-leguminous trees resulting from increased organic matter through litter fall and root turnover (Kellman, 1979; Young, 1989; Belsky *et al.*, 1989). Soil conservation is an extremely important aspect of windbreak plantings in the Sahel (Joseph, World Bank Afforestation Project Kano, Personal communication), and its benefits are well established.

1.3.7 Precipitation

Extensive areas of windbreaks may change precipitation on a macro-scale (Konstantinov and Struzer, 1965), although evidence for this is scarce. Distribution of precipitation within a windbreak system has caused large yield increases in the steppes of Russia that were attributed to even distribution of snow across fields giving a uniform soil water distribution (Konstantinov and Struzer, 1965; Scholten, 1988). Kort (1988), reviewing 97 different trials showed that on average yield increases of field and forage crops, where snow was a major component of the precipitation, was 20.8 %, but was only 12.5 % when snow was not present. Data from the Steppes of Russia has led to the conclusion that the effect of shelter increases in dry years (discussed further in Section 2.1). Interception of rain by a windbreak depends on the intensity of the storm, size and shape of canopy, and atmospheric demand (Rutter, 1975; Teklehaimanot, 1990), but is only a small component of the system water use under semi-arid conditions, because of the small canopy of the windbreak in relation to field size and the high intensity of storms (Darnhoffer *et al.*, 1989).

1.4 SUMMARY

Trees are required for both economic, social and ecological reasons in the Sahelian zone. Arnborg (1988) said that in the Sahel;

> *"The means and ultimate goal should be planting of trees and shrubs for protection of food crops and land, and for the production of fodder and wood."*

The planting of trees as windbreaks may provide one way of successfully introducing trees into farming systems. The benefits for the farmer in terms of tree products and reduced soil erosion leading to increases fertility are known. What is less clear is the response of crop growth to shelter. Generally yields increase behind shelter, but the reasons for the yield increase vary between trials. Water conservation is a popular reason for yield increases behind windbreaks, based on evaporation measurements, leading to the conclusion that sheltered yields should be larger in dry years and dry climates. However this does not seem to be the case (Section 1.3.1) and the energy balance equation (Section 1.3.2.2) shows that while evaporation may decrease in shelter transpiration increases, with increases being larger with higher stress. So if there is a response to shelter in the Sahel and water conservation is not the reason, then what causes the yield response?

The magnitude of competition between windbreak and crop is likely also to be larger in arid areas and has been shown to be important in alley cropping systems in semi-arid zones. How important is this for windbreaks, and if this is important can the competition be reduced by above or below-ground pruning? In order to determine this an idea of the relative importance of above and below-ground components of competition is necessary.

A third area of uncertainty is how much water the windbreak uses up? Trees often transpire more water than crops, and may transpire for the whole year. Little information is available on the amount of water transpired by windbreaks and its effect on the water balance of an area. This sort of information is vital for planners and managers of windbreak projects.

1.5 AIMS

This thesis aims to establish;

(i) Whether there is a net increase in millet yield behind a two row neem windbreak under Sahelian conditions.

(ii) Whether the growth response of the crop results from water conservation or from other changes in the microclimate.

(iii) Whether the decrease in yield near the windbreak results primarily from below-ground competition.

(iv) Whether windbreak transpiration constitutes a significant component of the water balance.

(v) Considerations for windbreak management in the Sahel.

This will be done by;

1) measuring the growth response of millet behind a windbreak (Chapter 2);

2) determining the magnitude of shelter and how it changes over the season (Chapter 4);

3) relating changes in the wind pattern to changes in the plant energy balance, and relating changes in microclimate to plant growth (Chapter 5);

4) calculating leaf and crop water use with distance behind the windbreak (Chapter 5);

5) calculating water transpired by the windbreak over the growing season and the whole year (Chapter 6 and Chapter 8);

6) quantifying competition for water and light between tree and crop, and effect on millet yield (Chapter 7); and

7) outlining under what conditions shelter will benefit crop growth, and the water use of a windbreak system over a year (Chapter 8).

Materials and methods are described for millet growth and harvest at the start of Chapter 2, for micrometeorological measurements in Chapter 3, and for tree measurements in Chapter 6. Chapters 2, 4, 5 and 7 commence with a review of relevant literature, and chapters containing experimental results contain a summary of results. Instruments designed and constructed at Edinburgh University are described in detail in Appendices III and IV, and Appendices II and V contain full data sets of millet yields and normalized wind speeds respectively.

1.6 SITE CHARACTERISTICS

1.6.1 Location

The trials were carried out at ISC, the Sahelian Centre of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Sadoré, Niger, West Africa. The farm is located 45 km south of the capital of Niger, Niamey, (13° 15' N, 2° 17' E), altitude 221 m (Figure 1.2).

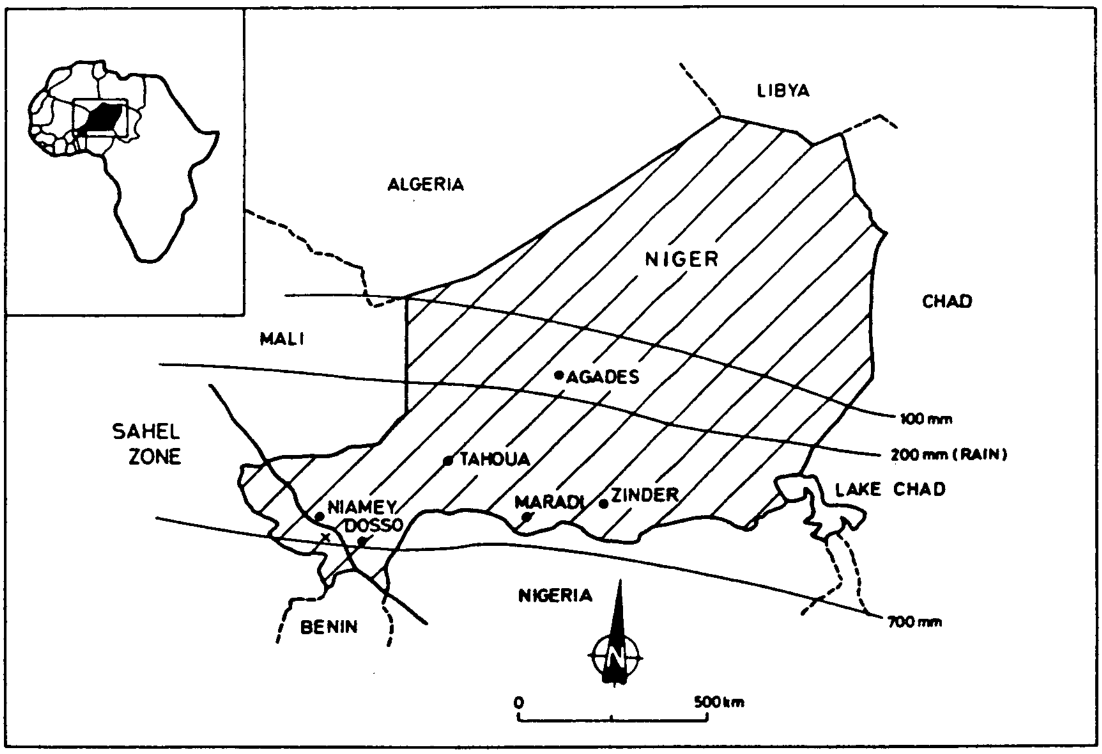


Figure 1.2 The republic of Niger showing the location of the ICRISAT Sahelian Centre (x). (Reproduced from Wallace *et al.*, 1986).

1.6.2 Climate

The Sahelian climate consists of three distinct seasons, a rainy season (June to September) during which most (> 90 %) of the rain falls, followed by a warm-dry season (October to mid-March), and a hot-dry season (mid-March to first rains). Mean annual rainfall is 550 mm, although total annual rainfall, distribution and onset of rains are all highly variable (Sivakumar, 1987).

Mean annual rainfall in 1988 and 1989 are given in Table 1.1 for two fields 1 km apart: (i) within the windbreak system and (ii) outside the influence of the windbreak, (see Figure 2.1 for location on farm). Rainfall distribution within the windbreak system and differences between rain falling within and outside the windbreak system are shown in Figure 1.3a - d.

Table 1.1 Total annual rainfall for 1988 and 1989 for Sadoré, Niger, inside and outside the windbreak system.

	Annual total (mm)		Rainfall during cropping season (mm)	
Position	1988	1989	1988	1989
Inside	694.3	467.5	641.2	385.5
Outside	668.9	485.0	624.3	404.0
Difference	25.4	-17.5	16.0	-18.5

Differences between rainfall inside and outside the windbreak system did not exceed 26 mm for the year, thus the influence on millet growth would have been small.

1.6.3 Soils

Trials were conducted on sandy alfisols of the Dayobu and Labucheri series, (West *et al.*, 1984). These soils are deep, yellowish-red sands, with an Ap horizon of

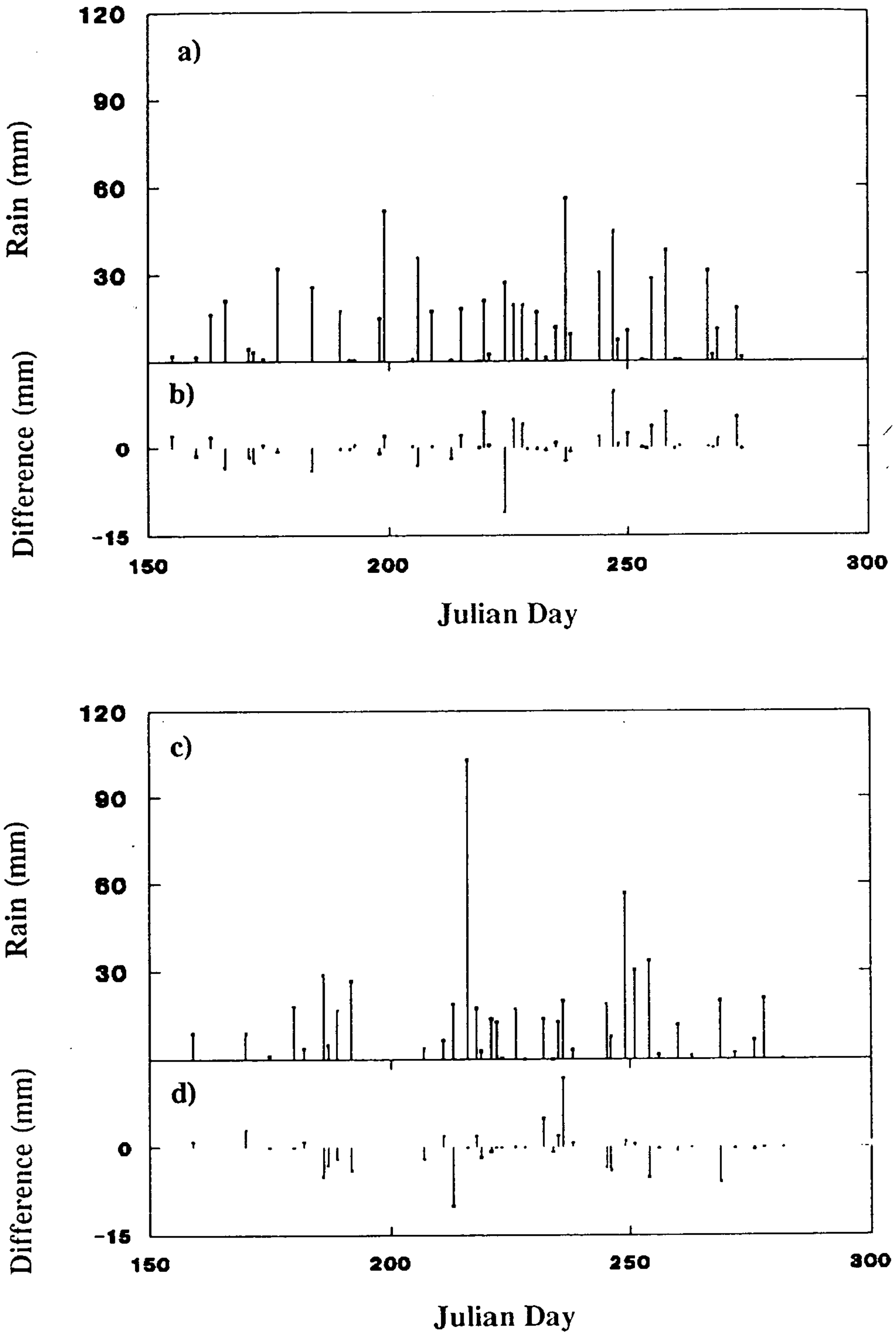


Figure 1.3 Rainfall patterns a) for 1988 within the windbreak system, b) difference in 1988 between rain falling within and outside the windbreak system, c) for 1989 within the windbreak system, d) difference in 1989 between rain falling within and outside the windbreak system.

around 30 cm and a B horizon extending to 1.8 m in all field trials. The gravelly C horizon extends to a depth of 4 to 6 m. Some physical and chemical characteristics of the Labucheri soil are given in Table 1.2.

Table 1.2 Chemical and physical properties of the Labucheri series soils (from West *et al.*, 1984).

Characteristic	Ap Horizon	B Horizon
Sand (%)	91.2	87.8
Silt (%)	4.7	4.7
Clay (%)	4.2	7.6
pH	4.9	4.9
CEC (meq 100 g^{-1})	1.3	1.3

meq 100 g^{-1} - milli equivalents per 100 g of dry soil
CEC - cation exchange capacity

The fields are flat (slope < 2^o), with free draining soils of low organic matter and fertility. Other soil characteristics can be found in West *et al.* (1984).

1.7 MILLET

Pearl millet (*Pennisetum typhoides* S. & H.) is a C4 tropical cereal that is grown as a subsistence crop by farmers over much of the semi-arid tropics. It is mainly grown where rainfall is inadequate for other cereals production, and can produce grain on 200 mm of rainfall, although it usually requires between 400 to 800 mm.

Two varieties of millet were used in the trials, Sadoré locale and C.I.V.T.. Sadoré locale is locally grown and originates from the west of Niger, it has a development cycle of 100 to 110 days. C.I.V.T. (Composite-Inter-Varietal de Tarna) is an improved variety, produced by crossing four Nigerien varieties and was selected for its higher grain yield. It has been in circulation since 1976 and has a developmental cycle of 90 to 95 days (ODA, 1987a; Moustapha, 1986).

1.8 NEEM

Neem (*Azardirachta indica* A. Juss) originates from the dry forests of the Indian subcontinent and is a member of the *Meliaceae* family. It was originally introduced to West Africa as an ornamental tree in the 19th century, and has become a popular tree in villages throughout the Sudano-Sahelian zone. It grows on annual rains of between 400 to 1150 mm, but can survive on substantially less. The neem tree retains its foliage throughout the year and so is often found in market places providing welcome shade during the hot season.

Neem is a multipurpose tree; its wood can be used for firewood, construction poles and furniture. It is dense, termite resistant and coppices freely and is often grown on an 8 to 10 year rotation. The fruit of the neem tree contains a seed which produces oil used for soap, lubricants and disinfectants. Azardirachtin can also be extracted from the seed and used as an insecticide. Leaves, twigs and neem cake (the residue of the seeds once oil has been extracted) have been used as fertilizers. The bark of the neem tree contains 12 to 14 % tannins; these can be extracted for the leather industry and discourage browsing of the bark by animals. However, leaves are browsed by cattle in India and East Africa, although West African varieties are only browsed under extreme circumstances. Neem is also revered in India and Africa for the variety of medicines it produces which cure complaints from skin infections to malaria (Ahmed and Grainge, 1985; Nair, 1988).

CHAPTER 2

THE EFFECT OF WINDBREAKS ON MILLET GROWTH AND YIELD

2.1 INTRODUCTION - CROP GROWTH BEHIND WINDBREAKS

Large differences in crop response to shelter have been reported, which is not surprising considering the wide variety of windbreak types, crop varieties, management systems and environmental conditions under which trials have taken place. The following section outlines some of these responses, more comprehensive reviews of the subject are given by Caborn (1957), Stoeckler (1962), Van Eimern *et al.* (1964), Grace (1977) and Kort (1988).

2.1.1 Effect of crop type

The 'most responsive' crops to shelter are often horticultural crops such as tobacco (*Nicotiana tabacum* L.), tea (*Thea sinesis* L.), lentils (*Lens culinara* Medic.) and fodder crops e.g. alfalfa (*Medicago sativa* L.), clover (*Trifolium* spp. L.) (Stoeckler, 1962; Sturrock, 1984; Baldwin, 1988). Many cereals are described as 'less responsive' e.g. spring wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.), with others thought to be 'moderately responsive', e.g. barley (*Hordeum sativum* Pers.) and millet (Kort, 1988).

A problem with averaging yield data from different environments is that much of the information concerning the differing crop responses to shelter are ignored. Brown and Rosenberg (1972), Kort (1988) and Sturrock (1984) have suggested larger benefits to crop production in drier years. This hypothesis is supported by yield data for a variety of crops from the USSR showing large yield responses to shelter in dry years (Van Eimern *et al.*, 1964) and reduction of evaporation behind windbreaks (Section 5.1.6). Stoeckler (1962) pointed out that maximum yields in dry years were found at distances from the windbreak where maximum snow had accumulated, ie. water availability was increased rather than transpiration being decreased. Percentage yield increases in dry years were higher often because unsheltered yields were so low, larger absolute yield increases were found in wet years (Stoeckler, 1962). The above responses demonstrate problems associated with inappropriate comparisons and conclusions drawn from areas where snow is important, are not relevant to the semi-arid tropics. Crop responses to shelter in the semi-arid tropics are presented in Table 2.1.

Table 2.1 Table of crop responses to shelter in semi-arid tropical environments

Source	Crop	Windbreak type	% increase	Comment
Rehman (1978)	winter wheat	1 row tree	7	Pakistan, irrigated
		2 row tree	15	
		3 row tree	13	
Reddi *et al.* (1981)	groundnut	4 row tree	42	mean 2 years
	p. p.	"	43	mean 2 years
	millet	"	63	rain - 696.1 mm
	millet	"	23	rain - 430.5 mm India, dryland
Long and Persaud (1988)	millet	2 row tree	26	Niger, dryland biomass inc. 73 %
Ujah and Adeyo (1984)	millet	10 row tree	14	Nigeria, dryland
Sheikh *et al.* (1984) (cited Kort, 1988)	spring wheat	(not known)	25	Pakistan, irrigated

continued

Vora	spring	2 row tree	23	India, dryland
et al.	wheat			biomass inc. 98 %
(1982)	mustard (pods)		13	biomass inc. 7 %

groundnut (*Arachis hypogea*)
inc. increase over unsheltered yields
p. p. - pigeon pea (*Cajanus cajan*)
mustard (*Brassica juncea*)

The overall results show net increases in crop yield with shelter from 7 % to 63 %, in semi-arid tropical environments. Some reasons for variability in crop response are outlined in the following sections.

Differences in responses to shelter of crop type may not be limited to microclimatic factors: Jaffe (1973) showed mechanical rubbing of leaves inhibited wheat growth by 11 %, considerably less than maize (28 %) and beans (*Phaseolus vulgaris* L.) (45 %). Storm events causing lodging may also reduce final yield (Sturrock, 1984).

2.1.2 Effect of windbreak type and management

Irrigation and shelter combined increase crop yields to a larger extent than the sum of the individual components (Sturrock, 1984; Barker *et al.*, 1989), which may result from reduced evaporative loss of irrigated water and increased stomatal conductance (Rosenberg *et al.*, 1966; Frank *et al.*, 1974). Shelter decreased yields in wet years (Shah, 1961; Sturrock, 1984), because of improved microclimate for fungal growth or insect infestation. Frank *et al.* (1974), Frank *et al.* (1977) and Carr (1985) reported yield increases behind windbreaks when moisture was available, whereas when water was scarce shelter reduced crop growth. Slat fences decrease yields less than tree windbreaks, which often reduce yields within a zone of 0.5*h* to 2*h* either side of the windbreak, (discussed further in Chapter 7).

2.1.3 Morphology and development

Shelter may affect the phenological development of crops, e.g. earlier fruit formation in cotton (*Gossypium hirsutum* L.) (Barker *et al.*, 1989), earlier flowering and maturation of grapes (Simon, 1977). Early flowering of sheltered maize (Zohar and Brandle, 1978), soybean (*Glycine max* (L.) Merr.) (Ogbuehi and Brandle, 1982) and millet (Oboho personal communication) have been reported.

Leaf area generally increases in shelter (Rosenberg, 1966; Brown and Rosenberg, 1972; Marshall, 1974; Frank *et al.*, 1977), leading to increased above ground biomass. Changes in harvest index in shelter have also been reported, with decreases for sheltered maize (Bates, 1911; Stoeckler, 1962), millet (Long and Persaud, 1988), and wheat (Vora *et al.*, 1982), and increases for soybeans (Ogbuehi and Brandle, 1982) and mustard (Vora *et al.*, 1982).

The importance of shelter for plant growth varies with average day temperature: winter cereals respond more than spring cereals (Stoeckler, 1962; Kort, 1988). Increased growth of tea in shelter was larger when average temperatures were 12 ^{o}C as opposed to 18 ^{o}C (Carr, 1985) and cotton responded better to shelter with earlier planting because of the lower average temperatures at the beginning of the year (Barker *et al.*, 1989).

2.2 MATERIALS AND METHODS

2.2.1 Experimental aims

In the present work three trials were run for two years. 'Standard' investigated changes in microclimate and growth with distance from the windbreak, on an unmanaged neem windbreak encompassing both competition near the windbreak and shelter in its lee. 'Density' investigated the effect of changing the porosity of the lower part of the windbreak, reducing air flow under the canopy. 'Competition' allowed the separation of above- and below-ground components of windbreak - crop competition, using a plastic barrier (discussed in Chapter 7). A description of the windbreaks is given in Section 6.2.1.

2.2.2 'Standard'

Fields 3a (windward, but sheltered by the first windbreak in the system which was 25*h* away), 3b (sheltered) and 7b2 (unsheltered control) were used in both 1988 and 1989 (Figure 2.1). In 1988, 60 m of 3b was sown with millet, with the rest of the field in a millet/cowpea intercrop; in 1989, the whole field sown with millet. Millet is sown in hills of 7 to 10 plants per hill, and once the crop is established the millet plants are thinned to about 3 plants per hill. Agronomic details of the trial

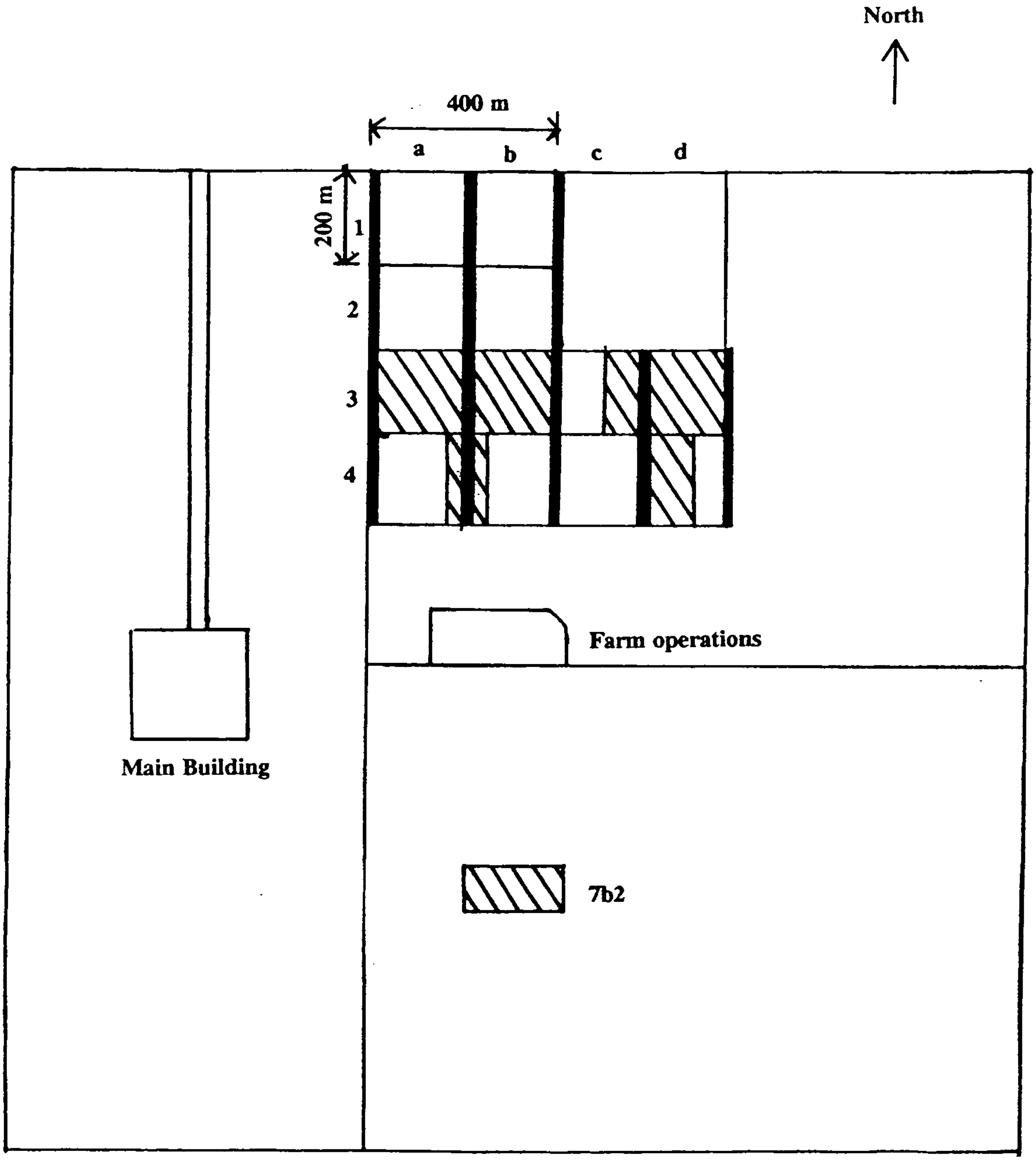


Figure 2.1 Layout of farm at ISC. Fields used for trials in 1988 and 1989 (▨), position of windbreaks (▮).

are given in Table 2.2.

Measurements were taken at distances of 1*h*, 3*h*, 6*h*, 10*h* and unsheltered control where *h* = height of the windbreak, *h* being 5 m in 1988 and 6 m in 1989 (plot layout, Figures 2.2a - b).

Table 2.2 Agronomic details of trial 'Standard' 1988 and 1989

	1988	1989
Length of 3a	100 m	100 m
Length of 3b	60 m	200 m
Sowing date	dry sown (12/6)*	5/7
Variety	Sadoré Locale	Sadoré Locale
P_2O_5	40 kg ha^{-1}	40 kg ha^{-1}
N as CAN in 2 dressings	45 kg ha^{-1}	45 kg ha^{-1}
Plant density	22 000 hill ha^{-1}	17 000 hill ha^{-1}
Harvest date	27/9	20/10(3b),30/10(7b2)
Sequential sampling		
Frequency	every 2 weeks	weekly
Treatment distances (in multiples of *h*)	1 ,3 , 10, control	1 ,3 ,6 ,10 ,20 control
Number of reps.	5	5
Plot size per rep	2.72 m^2	4.71 m^2

Final Harvest		
Number of reps.	6	5
Plot size	25 m^2	11.25 m^2
Treatment distances (in multiples of *h*) (Field number in brackets)	1 ,3 ,6 ,10 - (3b) control - (7b2)	0.5, 0.9, 1.3, 1.7, 2, 2.4, 2.8, 3, 4, 6, 10 - (3a and 3b) 5, 7, 8, 15, 20 - (3b only), control - (7b2)

* first rains CAN - Calcium ammonium nitrate

2.2.2.1 Sequential Growth Measurements

Millet growth was measured at regular intervals (Table 2.3): 6 hills and 8 hills per plot were sampled in 1988 and 1989, respectively.

Plant height and tiller number : Plant height was taken as height of highest millet leaf or panicle for each hill, measured with a rule (± 1 cm). Plants were straightened before measuring if necessary. Tiller and panicle numbers for each hill were counted in 1988 but not in 1989.

Dry weight and leaf area : Leaf, stem and panicle material from each plot was separated by hand. A subsample of 5 000 cm^2 leaf area of fresh leaf material was measured using a leaf area meter (Licor 3100, LI-COR Inc., Lincoln, NE, USA). Samples were dried at 70 ^{o}C for 48 hours and weighed in their sacks, after which sack dry weight was taken. Specific leaf area (SLA) of the subsample was calculated by dividing area by dry weight. SLA was multiplied by total leaf dry weight of the sample to give total leaf area of the sample (A_{sam}) m^2. Leaf area index of the millet crop (L) was calculated using equation 2.1;

$$L = (A_{\mathrm{sam}}\ N_{\mathrm{hec}})\ /(N_{\mathrm{sam}}\ 10\ 000) \qquad (2.1)$$

where N_{hec} is number of hills per hectare and N_{sam} is number of hills in the

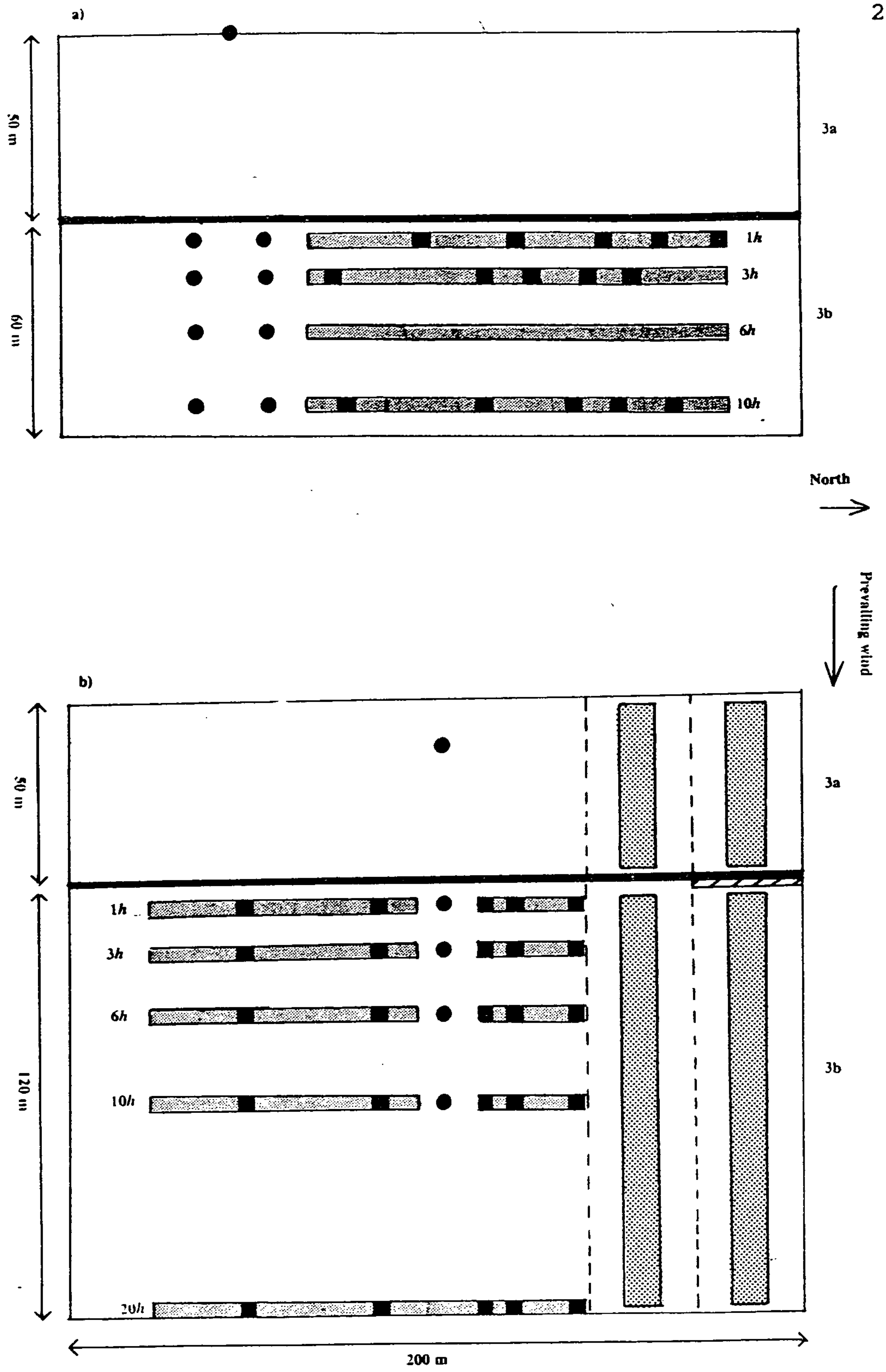


Figure 2.2 Field layout for 'Standard' fields 3a/3b, a) 1988 and b) 1989. Sequential and final harvest samples were taken from within the shaded area. In 1988 samples were taken at 1*h*, 3*h* and 10*h* behind the windbreak, at randomly selected positions along the windbreak. In 1989 five randomly selected transects were sampled. Sampling pattern is indicted by (■), and positions of micrometeorological stations (●). One replicate from 'Density' was installed on 3a/3b (see Fig 2.3 for details).

sample.

Table 2.3 Dates, and number of days after sowing (DAS) for the sequential samples taken in 1988 and 1989.

Sample Number	1988 date	DAS	1989 date	DAS
1	8/7	27	10/8	36
2	27/7	46	17/8	43
3	11/8	61	25/8	50
4	29/8	79	30/8	56
5	16/9	107	7/9	62
6			14/9	71
7			28/9	85

2.2.2.2 Final harvest

Number of hills per plot was recorded, after which panicles were harvested and stover (stem and leaf) cut at ground level. Millet panicles were separated into grain filled and empty, counted and dried at 70 ^{o}C for 48 hours, weighed, then threshed by hand. Total grain weight and mean 1000 grain weight was measured for each sample.

Stover samples were weighed wet in the field, using a 25 kg balance (accuracy ± 100 g). A 2 kg subsample was taken using a 10 kg balance (accuracy ± 20 g) and dried at 70 ^{o}C for 48 hours. Total dry weight of the sample was calculated from total fresh weight and water content of the subsample.

2.2.3 'Density'

Locally manufactured millet straw matting was attached to a series of metal poles and the windbreak trees on the eastern side of the windbreak to reduce windbreak porosity below the canopy (0 to 2 m). In 1988 two replicates of 50 m and, in 1989 four replicates of 30 m (including a barrier on field 3a/3b, Figure 2.2b) were used

(Figures 2.3a - b). Measurements at final harvest were taken on both sides of the windbreak to evaluate the effect of the easterly storm winds, as opposed to the prevailing westerly wind on crop yield. Agronomic details are given in Table 2.4, final harvest was carried out as described in Section 2.2.2.2.

Table 2.4 Agronomic details of trial 'Density' for 1988 and 1989

	1988	1989
Length of 3c	60 m	60 m
Length of 3d	60 m	200 m
Sowing date	25/6	19/6
Variety	C.I.V.T.	Sadoré locale
P_2O_5	40 kg ha^{-1}	40 kg ha^{-1}
N as CAN	45 kg ha^{-1}	45 kg ha^{-1}
Plant density	22 000 hill ha^{-1}	17 000 hill ha^{-1}
Harvest Date	16/9	14/10
Treatment distances (in multiples of *h*) (Field number in brackets)	1, 3, 6, 10 - (3c and 3d)	0.5,0.9,1.3,1.7, 2.0,2.4,2.8,3.0, 4,6 - (3c and 3d) 5,7,8,10,15, 20 - (3d only)
Number of reps.	2	4
Plot size	15 m^2	11.25 m^2

2.2.4 'Competition'

Separation of millet and neem root systems was made by digging a 1.2 m deep trench 0.5 m wide, 1.0 m from the tree line, cutting existing roots. Root re-growth was prevented by lining the trench with heavy gauge plastic sheeting and refilling with soil, similar techniques have been used by Willey and Reddy (1981) in intercropping and Corlett (1989) in agroforestry. Fields used were 4d in 1988 and, 4d and 4b in 1989, plot layout is shown in Figures 2.4a - b. Observations made on the trenches when relined in 1989 showed no penetration of the barrier by tree

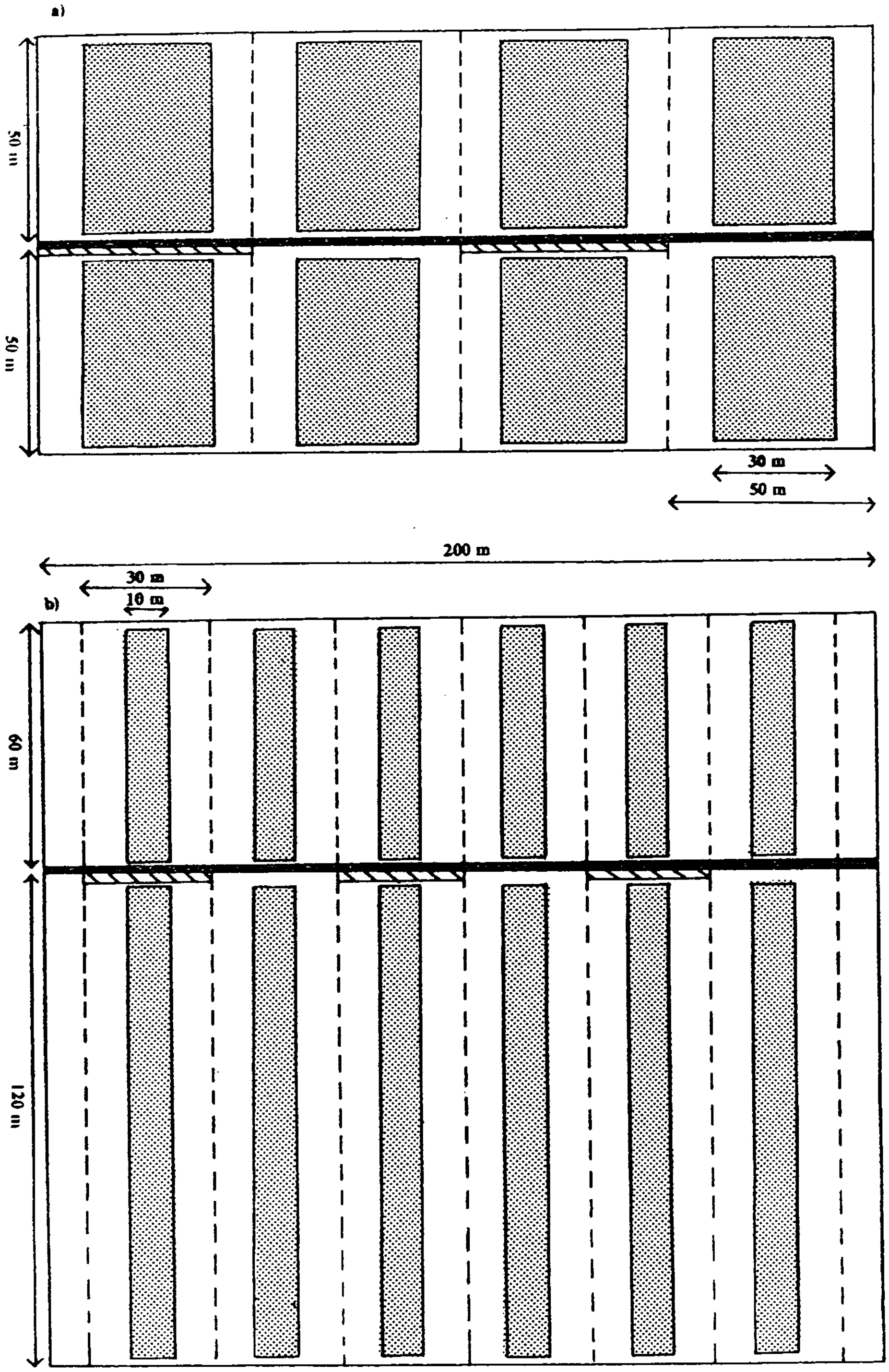


Figure 2.3 Field layout for 'Density' fields 3c/3d, a) 1988 and b)1989. Millet straw barriers are marked (▨), final harvest samples were taken from the shaded area, three and one samples were taken from each replicate in 1988 and 1989, respectively.

roots. Details of the trial are given in Table 2.5.: final harvest was as Section 2.2.2.2.

Table 2.5 Agronomic details of trial 'Competition' 1988 and 1989.

	1988	1989
Length of 4d	70 m	70 m
Length of 4b	-	20 m
Sowing date	18/6	19/6
Variety	C.I.V.T.	Sadoré Locale
P_2O_5	40 kg ha^{-1}	40 kg ha^{-1}
N as CAN	45 kg ha^{-1}	45 kg ha^{-1}
Plant density	22 000 hill ha^{-1}	17 000 hill ha^{-1}
Harvest Date	16/9	14/10
Treatment distances	0.6, 1.6, 2.6, 4.6	0.6,1.0,1.3,1.7
(in multiples of *h*)	6.6 - (4d)	2.1,2.5,2.8,
(Field number in brackets)		3.1 - (4a and 4d)
		4,5, 6 - (4d only)
Number of reps.	3	6
Plot size	7.5 m^2	11.25 m^2

2.3 STATISTICAL ANALYSIS

Most experimental designs include randomisation and blocking of treatments to allow for the effect of fertility and other gradients across a field. In windbreak trials it is not possible to randomise treatment distances from a windbreak with respect to each other. Furthermore, since the area of influence of the windbreak is *a priori* unknown, a proper control may have to be a very long way from the windbreak. So comparisons between a control (e.g. a field outside the influence of the windbreak) and the windbreak field can be only rarely be spatially replicated, because of the large field size necessary to allow the effect of the windbreak to be measured, and the realistic size of a trial on a research station. The problem of non-randomness of the data must be considered when applying statistical methods.

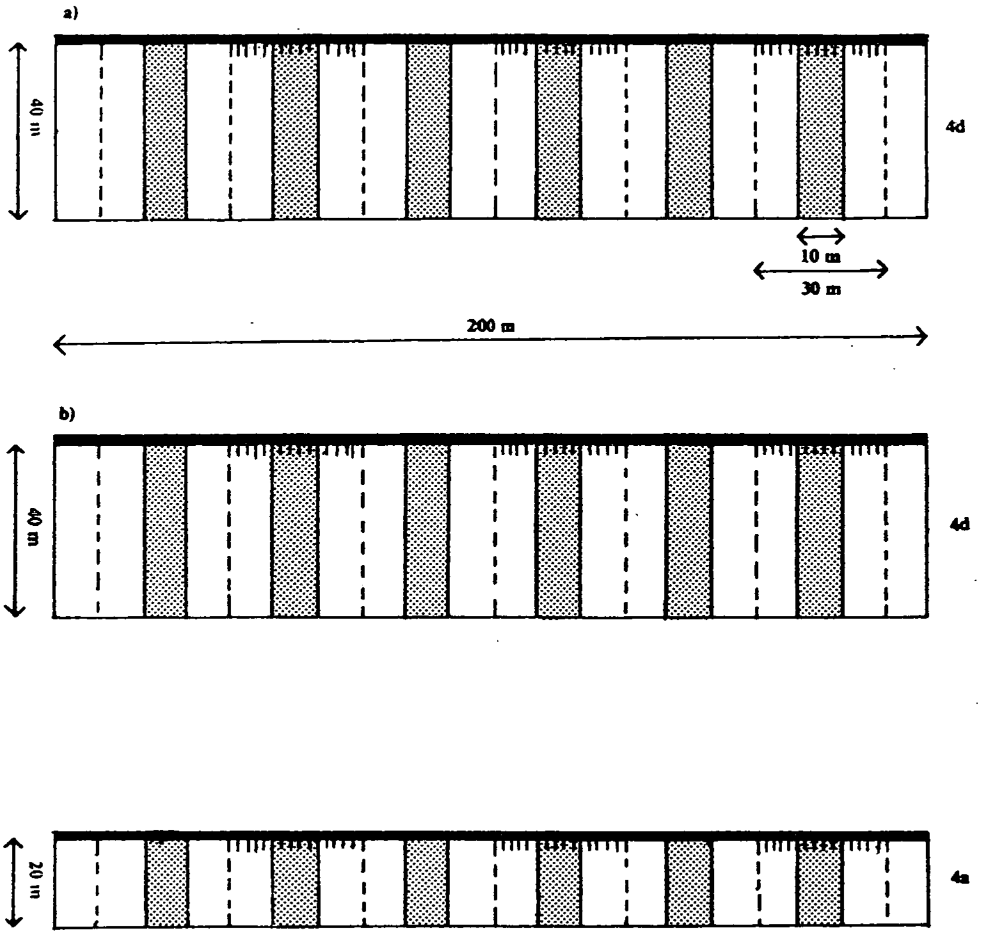


Figure 2.4 Field layout for 'Competition' a) in 1988, fields 4d b) in 1989 fields 4b and 4d. Root pruning is indicated by (┬┬┬), final harvest samples were taken from the shaded area, two and one samples were taken for each replicate in 1988 and 1989, respectively.

Analyses undertaken have aimed to minimise the problem of non-random sampling by both comparing individual populations and by analysing trends with distance from the windbreak using regression analysis.

If a specific treatment distance from the windbreak comprises a discrete population, the Tukey test can be used to test if the means of two samples are significantly different. This test was used for comparison of sequentially sampled and final harvest data between plots at different distances. The significance of differences between the control and $3h$ and other distances from the windbreak were calculated at the 5 % level and are given in Appendix II, Tables II.1 - II.13, in the sig from cont, and sig from 18/15 m ($3h$) rows.

Standard errors of means (s.e.) were calculated from variances of data sets with distances from the windbreak as treatments, as shown in Table 2.6, for a data set with n observations and t treatment distances.

Table 2.6 Analysis of variance for millet growth.

Source of Variation	d.f.	S.S.	M.S.
Treatment	$t - 1$	a	$a/t - 1$
Error	$n - t$	b	$b/n - t$

d.f. - degrees of freedom

S.S. - sums of squares

M.S. - mean square

Where variance (s^2) is $b/(n - t)$, and standard error (s.e.) is $\sqrt{(s^2/n)}$, assuming that s.e. is independent of distance from the windbreak.

Changes in yield with distance from a windbreak may not conform to a simple mathematical relationship, because yield depends on a combination of different processes. The yield response to distance from a windbreak may start linear ($y = a + bx$), or asymptotic ($y = a\ (1 - e^{-cx}) + b$), reaching a maximum, then decrease to a constant value towards the centre of the field. Choice of the correct equation was not obvious, so a cubic polynomial of the form $y = a + bx + cx^2 + dx^3$ was fitted. Whilst this curve does not have any biological significance, it allowed comparison between treatments. Sufficient treatment distances to fit valid curves were only available for the 1989 final harvest data.

These curves were tested as to whether a significantly larger amount of the residual variation was explained by fitting separate response curves for each treatment, compared to a combined response curve, using the method described below.

A curve with p parameters was fitted to two data sets from treatments T1 and T2, with residual sums of squares for T1 and T2, of d with $(n_1 - p)$ d.f. and e with $(n_2 - p)$ d.f. respectively, where n_1 and n_2 are the number of observations of T1 and T2. The curve fitted to the complete data set (T1 + T2) had a residual sum of squares of f with $(n_1 + n_2) - p$ d.f.. The S.S. of the individual lines were added, giving $(d + e)$, (Table 2.7). F determines whether the difference between the two individually fitted curves is significantly different from zero (Wardlaw, 1987).

Table 2.7 Analysis of variance table for comparison of two polynomials.

Source of variation	d.f.	S.S.	M.S.
residual T1	$n_1 - p$	d	$d/(n_1 - p)$
residual T2	$n_2 - p$	e	$e/(n_2 - p)$
residual (T1 + T2)	$(n_1 + n_2) - p$	f	$f/(n_1 + n_2) - p$
res. T1 + res. T2	$(n_1 + n_2) - 2p$	$d + e$	s^2
	$s^2 = (d + e)/((n_1 + n_2) - 2p)$		
difference	p	$(d + e) - f$	$((d + e) - f)/p$

F is calculated by dividing the mean square of the difference by s^2 with p and $((n_1 + n_2) - 2p)$ d.f.. s.e. can be calculated from $\sqrt{s^2/(n_1 + n_2)}$ and gave values very similar to those calculated by analysis of variance (Table 2.6). Values of s.e. in

Tables II.1 - II.18, Appendix II were calculated by this analysis of variance method to maintain consistency between data sets.

2.4 RESULTS AND DISCUSSION

Millet growing in plots at distances of 1*h*, 3*h*, 6*h*, 10*h*, 20*h* from the windbreak and in the control field are referred to as 1*h*, 3*h*, 6*h*, 10*h*, 20*h* and control. Complete tables of results are presented in Tables II.1 - II.12, Appendix II. The growth of millet on the unsheltered field (control) is indicated in the graphs by the unattached point with error bars showing ± one standard error of the complete data set.

2.4.1 Sequential sampling 'Standard'

2.4.1.1 Results 1988

Leaf Area Index : The most rapid initial development of leaf area index (*L*) occurred at 3*h*, with *L* approximately three times that at 1*h* and control (Figure 2.5a). Differences in *L* between 3*h* and the control were smaller by 46 DAS (Figure 2.5b) with no significant differences in *L* across the field by 61 DAS (Figure 2.5c). Decrease in *L* at 79 DAS was largest at 3*h* (1.57), and smallest in the control (0.15), making *L* higher in the control field than the sheltered field (Figure 2.5d). The reduction in *L* near the windbreak was largest at the start of the season.

Specific Leaf Area : Specific leaf area (SLA) decreased with leaf development, from 236 cm^2 g^{-1} to 134 cm^2 g^{-1} over the season. SLA at 1*h* was significantly higher than the rest of the field in the middle of the season.

Plant height : Plants at 3*h* were significantly taller than at 1*h* and substantially taller than the millet on the other plots at 27 DAS, (Figure 2.5e). Subsequent samplings showed a reduction in this advantage (Figures 2.5f - g), although 3*h* was 0.44 m taller at 61 DAS than the rest of the field, perhaps as a result of earlier stem elongation. Height differences at 79 DAS were not significant, with panicle heights at final harvest reaching 3.2 m at 3*h* and the control.

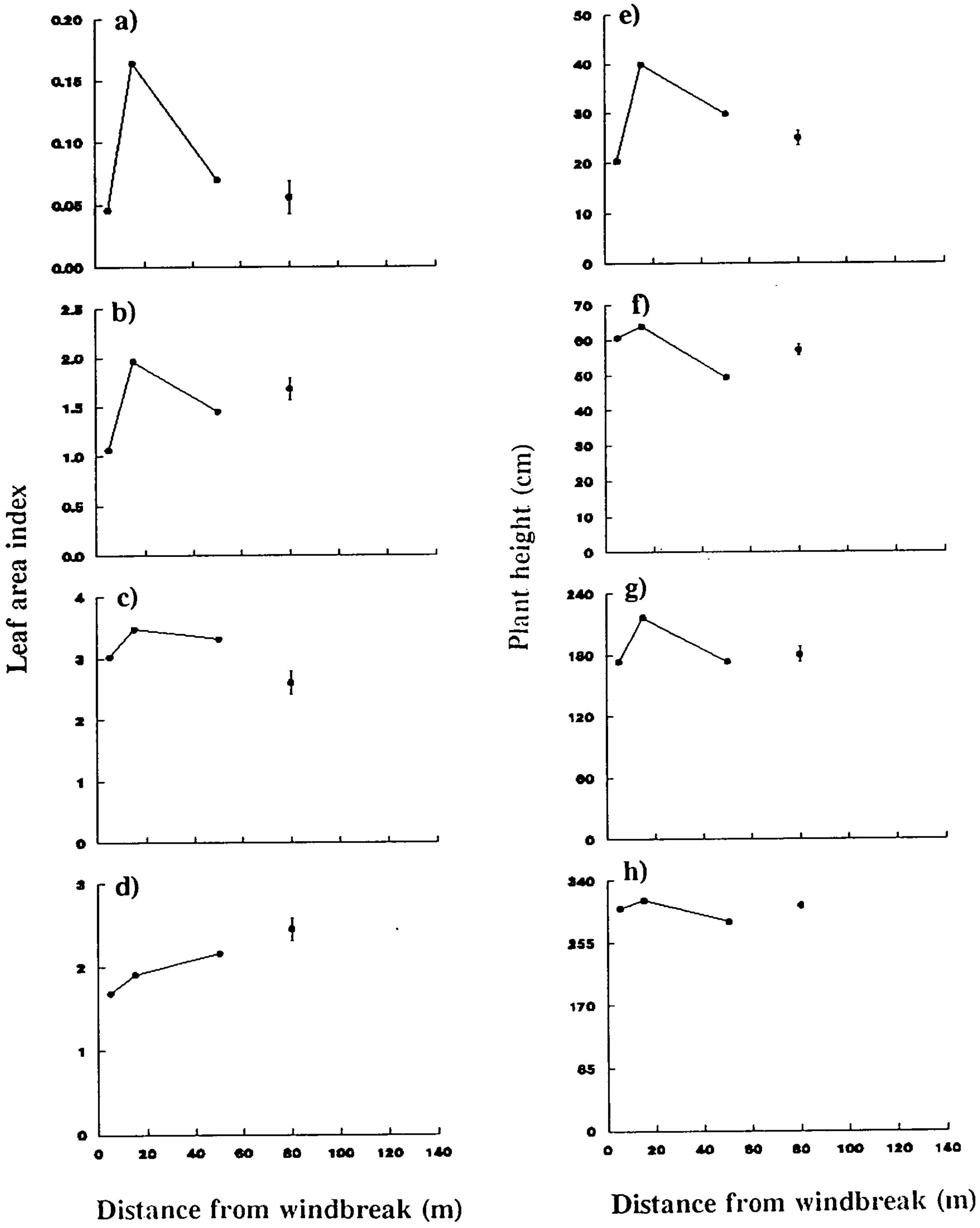


Figure 2.5 Millet sequential sampling 1988; Leaf area index at a) 27 DAS, b) 46 DAS, c) 61 DAS, d) 79 DAS; Plant height at e) 27 DAS, f) 46 DAS, g) 61 DAS, h) 79 DAS. Unattached point indicates value on control field, error bars indicate ± 1 s.e, (*n* = 5).

Tiller and Panicle Number : Tiller numbers were significantly higher at 3*h* than 1*h* with about 1.2 to 1.7 more tillers per hill than other plots. Tiller numbers increased rapidly on the control so that at panicle emergence (61 DAS) significantly more tillers were found on the control than sheltered field, a difference that was maintained until 79 DAS. The sheltered field had around 5.5 tillers and 3.2 panicles per hill, compared to 7.0 tillers and 3.6 panicles on the control, giving the control significantly more panicles per hill than the sheltered field at final harvest.

Leaf and stem dry weight, and biomass : Leaf dry weights (Figures 2.6a - d) were significantly higher at 3*h* than all other positions at 27 DAS, with the difference decreasing over the season. By 46 DAS leaf weight at both 3*h* and control were significantly larger than 1*h*, but by 61 DAS differences were no longer significant. Stem dry weights (Figures 2.6a - d) at 3*h* were significantly larger than in the rest of the field at 27 DAS. The differences in both stem dry weight and biomass, between 3*h* and the control had disappeared by 46 DAS (Figure 2.6e - h). No significant differences were calculated in either stem or biomass between distances at the end of the season, despite yield differences at 79 DAS between biomass at 3*h* and 1*h* of 1.9 t ha^{-1} and 3*h* and 10*h* of over 1.4 t ha^{-1}. By final harvest, biomass of both control and of 3*h* was over 9.5 t ha^{-1}; at 1*h* and 10*h* biomass was 7.26, and 8.62 t ha^{-1}, respectively.

Panicle Dry Weight : Panicle emergence had occurred by 61 DAS at all distances from the windbreak except at 1*h* (Figure 2.6g - h). By 79 DAS panicle weights at 3*h* were 1.07 t ha^{-1} with 1*h* being 36 % lower. Control panicle weight at the end of the season (3.14 t ha^{-1}) was significantly higher than 1*h*, and 0.5 t ha^{-1} more than 3*h*.

2.4.1.2 Results 1989

Leaf Area Index : Leaf area developed faster at 3*h* and 10*h* than at 1*h*, 6*h* and the control until 50 DAS (Figures 2.7a - c). At 50 DAS L at 3*h* was significantly higher than control, double that at 1*h* and by 56 DAS L at 3*h* had tripled L at 20*h* and control (Figure 2.7d). L at 3*h* reached a maximum of 2.5 at 62 DAS, but subsequently decreased. The decrease in L occured after 71 DAS at 6*h*, 10*h* and the control.

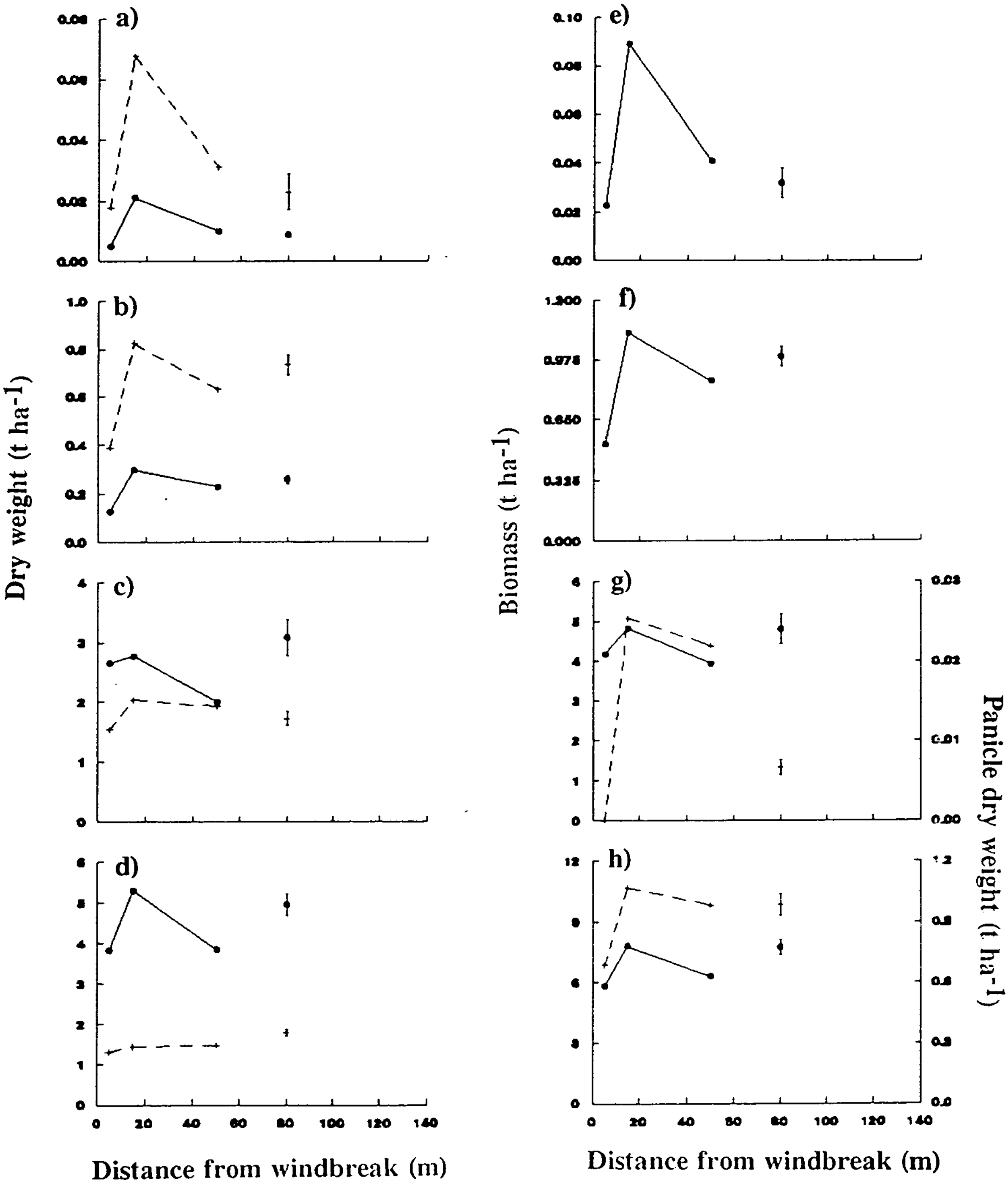


Figure 2.6 Millet sequential sampling 1988; Leaf dry weight (- - -) and stem dry weight (—) at a) 27 DAS, b) 46 DAS, c) 61 DAS, d) 79 DAS; Biomass (—), and panicle dry weight (- - - -) at e) 27 DAS, f) 46 DAS, g) 61 DAS, h) 79 DAS. Unattached point indicates value on control field, error bars indicate ± 1 s.e, (n = 5).

Between 62 DAS and 85 DAS (Figures 2.7e - g), *L* decreased at 3*h* (0.73), 1*h* (0.57) and 6*h* (0.33), and increased at 10*h* (0.22), 20*h* (0.001) and control (0.02).

Specific Leaf Area : Specific leaf area decreased over the season and behind the windbreak towards 10*h* after 43 DAS. SLA increased towards 20*h* and control, with similar values SLA at at 20*h* and control. Higher values of SLA were found at 1*h* than 10*h* after 50 DAS, which continued throughout the season to 85 DAS.

Plant Height : Millet heights (Figures 2.7a - g), at 3*h* and 10*h* were significantly higher than those at 20*h* at 36 DAS, and larger than 1*h*, 6*h* and control (Figure 2.7a). Differences in height between 6*h* and 10*h* decreased until stem elongation at 56 DAS (Figures 2.7b - c), where the rapid increase in plant height at 3*h* and 10*h*, suggest that 6*h* was developmentally retarded (Figure 2.7d), and made the millet at 3*h* and 10*h* significantly taller than control and 20*h*. By 62`DAS millet at 3*h* was over 0.6 m taller than at 10*h* and 20*h* and, 1.0 m taller than control. Differences in plant height within the windbreak system were smaller by 85 DAS although plants at 1*h*, 20*h* and control were shorter.

Leaf and stem dry weight, and biomass : Leaf dry weights were higher at 3*h* and 10*h* than 1*h*, 6*h* and control, at 36 DAS and 43 DAS (Figures 2.8a - g). The differences between 10*h* and 6*h* had disappeared by 50 DAS. By 56 DAS leaf weight at 3*h* was significantly larger than at 1*h*, 20*h* and control (Figure 2.8d). Leaf dry weight at 3*h* continued to increase reaching twice that at 10*h*, 20*h* and control by 62 DAS. Slower growth at 10*h* than 6*h* and 1*h* over the period 50 to 62 DAS meant that leaf weight at 6*h* exceeded that at 10*h*. The decrease in leaf production and rapid senescense at 3*h* in subsequent periods resulted in a reduction of the leaf weight differences within the field by 85 DAS (Figure 2.8g).

The stem dry weight (Figures 2.8a - g) reduction at 6*h* which disappeared by 50 DAS reappeared at 56 DAS, reflected in plant height observations (Figure 2.7d), and suggested that the higher stem weight at 10*h* resulted from earlier stem elongation. Larger stem weight and biomass (Figures 2.9a - g), were found throughout the season at 3*h*, with the largest differences at 62 DAS. Differences

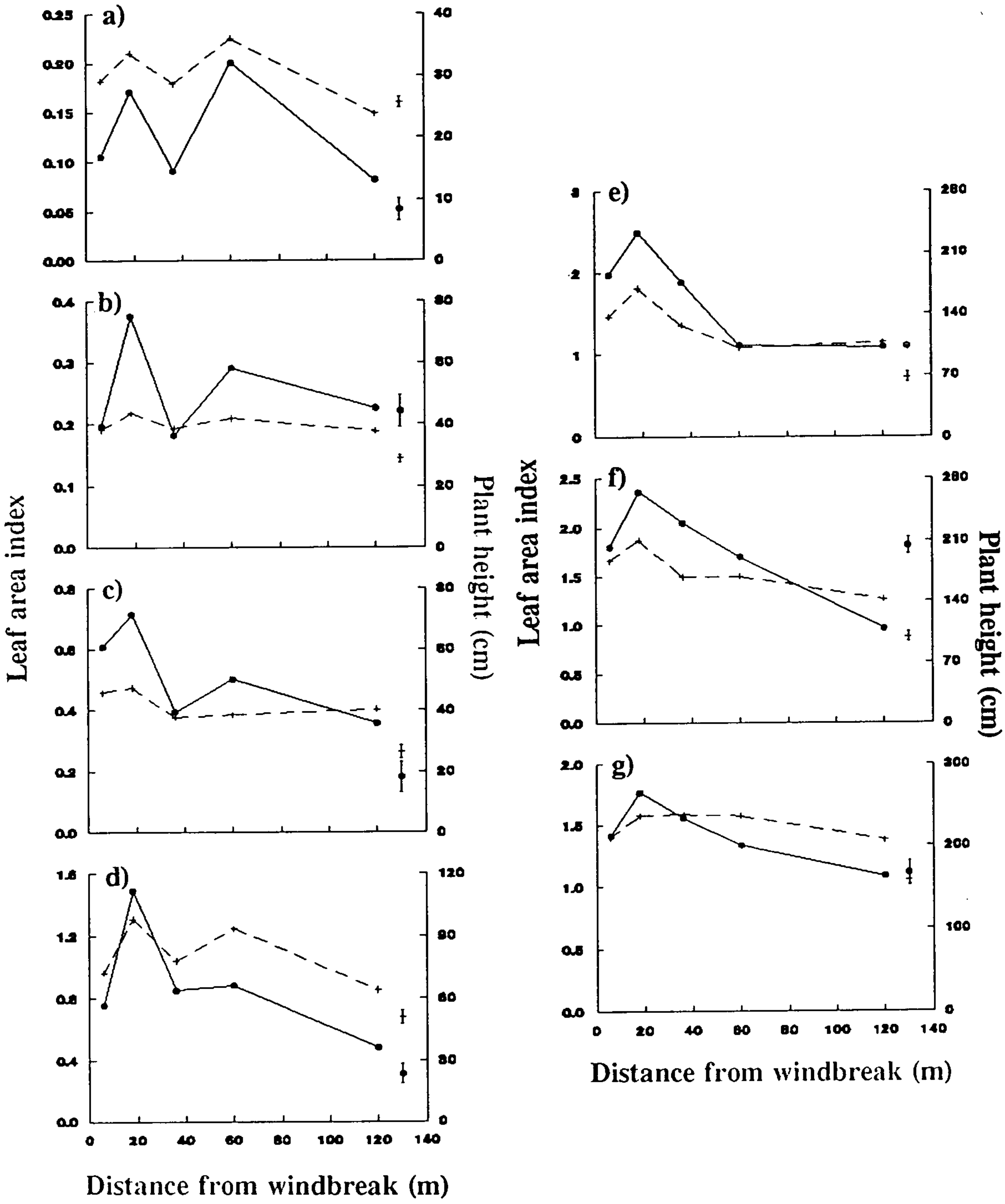


Figure 2.7 Millet sequential sampling 1989; Leaf area index (——) and plant height (---) at a) 36 DAS, b) 43 DAS, c) 50 DAS, d) 56 DAS, e) 62 DAS, f) 71 DAS, g) 85 DAS. Unattached point indicates value on control field, error bars indicate ± 1 s.e., (n = 5).

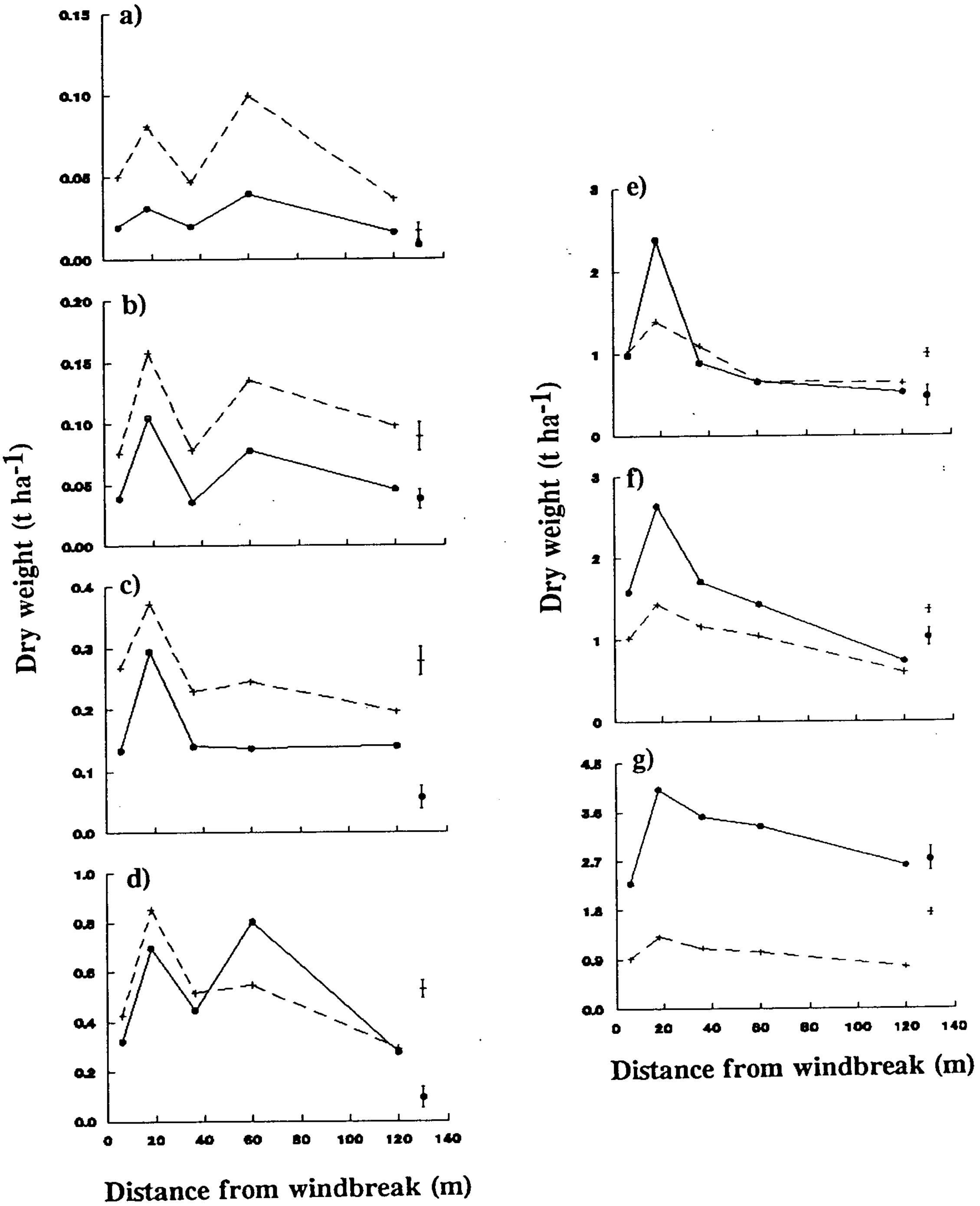


Figure 2.8 Millet sequential sampling 1989; Leaf dry weight (----) and stem dry weight (——) at a) 36 DAS, b) 43 DAS, c) 50 DAS, d) 56 DAS, e) 62 DAS, f) 71 DAS, g) 85 DAS. Unattached point indicates value on control field, error bars indicate ± 1 s.e., (n = 5).

between in biomass between 3*h* and the rest of the field decreased after this date. By 71 DAS biomass at 3*h* was significantly larger than at 10*h*, 20*h* and control, whereas by 85 DAS there were no significant differences, despite there being 2.6 t ha^{-1} more biomass at 3*h* than 1*h*.

Panicle Dry Weight : Panicle dry weight at 62 DAS was low at 6*h* following a similar pattern to leaf and stem weights at the beginning of the season. The pattern of panicle weights did follow the pattern of biomass by 71 DAS (Figure 2.9e - g), and by 85 DAS panicle weights at 3*h*, 6*h* and 10*h*, were similar, with 1*h*, 20*h*, and control having 69 %, 52 % and 52 % of the panicle weight at 3*h*, respectively.

2.4.1.3 Summary 1988

The unsheltered millet at the start of the season was damaged by violent sandstorms which reduced its leaf area, dry matter and height at 27 DAS. Millet at 3*h* benefitted from shelter, maintaining a larger leaf area which increased light interception and biomass accumulation. Rainfall in 1988 was over 650 mm and well distributed over the season (Figure 1.3a), allowing recovery of the unsheltered control millet by 46 DAS, suggesting that the physical damage from the sandstorm did not substantially reduce subsequent plant growth. Reduction of growth near the windbreak may have resulted from competition, which was most acute at the start of the season (Section 7.3.1). Growth at 10*h*, was faster than 1*h* but slower than 3*h* probably resulting from changes in microclimate (Section 5.2.3).

There were more tillers per hill on the control field than behind the windbreak at 61 DAS, resulting in more panicles per hill at final harvest. This may have resulted from early season sand blast damage to the main stem, or lower leaf temperatures (Section 5.2.3). Increased tillering meant that by 61 DAS biomass on the control equalled that at 3*h*, although *L* was lower. However, after panicle emergence which occurred earlier at 3*h* than on the control, leaves senesced rapidly at 3*h* while leaf area increased on the control. Slower growth at 1*h* occured throughout the season being more significant at the start of the season. Results are discussed in relation to the microclimate measurements in Chapter 5.

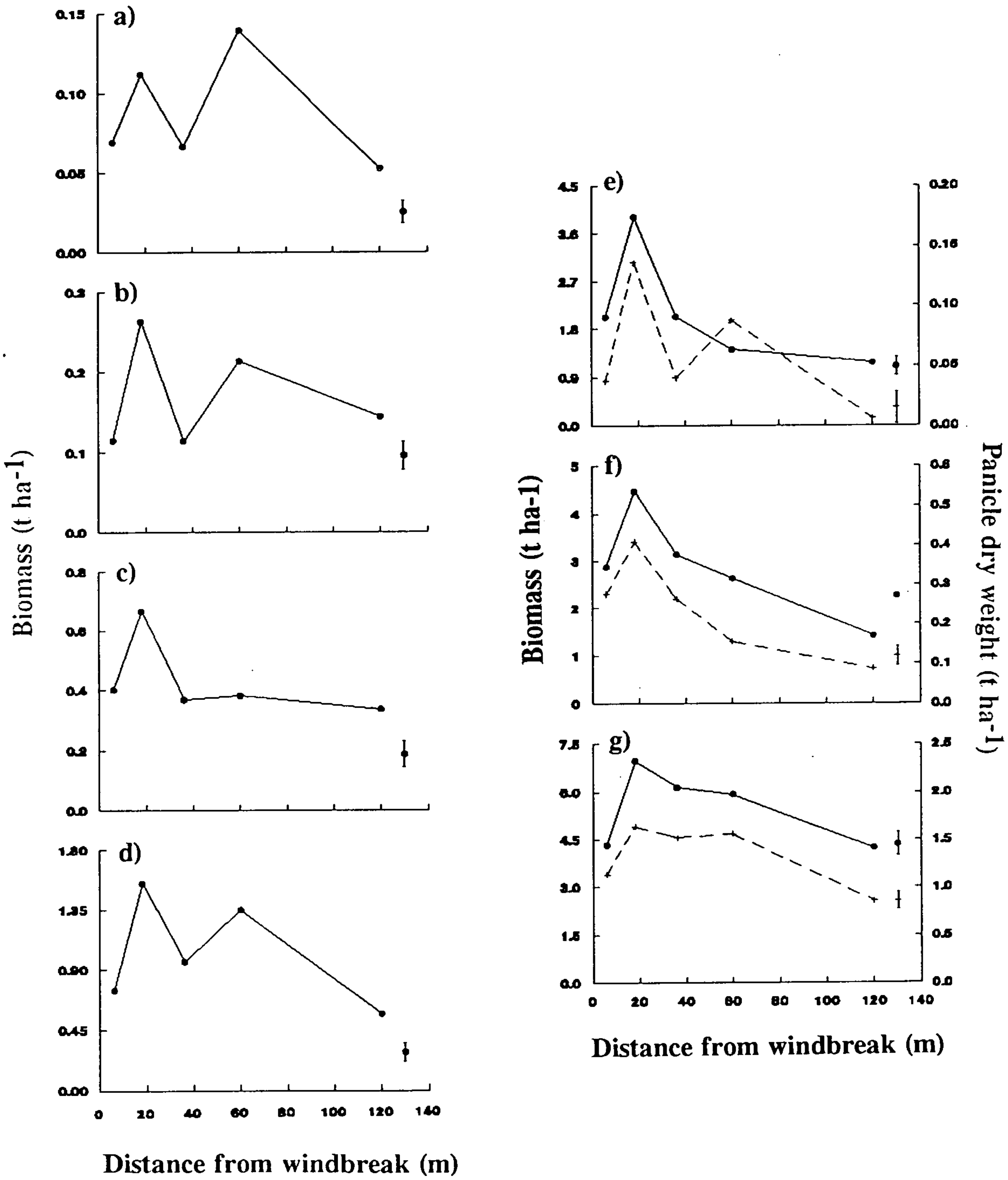


Figure 2.9 Millet sequential sampling 1989; biomass (——) and panicle dry weight (---) at a) 36 DAS, b) 43 DAS, c) 50 DAS, d) 56 DAS, e) 62 DAS, f) 71 DAS, g) 85 DAS. Unattached point indicates value on control field, error bars indicate ± 1 s.e., (n = 5).

2.4.1.4 Summary 1989

The later sowing date in 1989, combined with an extended drought period after the first series of rains (Figure 1.3b), limited leaf area development at the start of the season, reducing vegetative growth.

Reductions in leaf area and leaf and stem dry weight occurred at *1h*, *6h* and *20h* at the start of the season. Differences in leaf area and weight between *6h* and *10h* decreased steadily up to 50 DAS, when differences in plant height and weight between *6h* and *10h* were small. By 56 DAS stem elongation had occured at *3h* and *10h*, but not at *6h* as suggested by the larger height and stem weight, although leaf weights were similar at *6h* and *10h*. In subsequent harvests these differences were reversed indicating substantially better growth at *6h* than *10h*. Earlier panicle emergence at *10h* and *3h* than *6h* (61 DAS) suggest delayed development at *6h*, since its biomass was larger than at *10h*. By 71 DAS panicle weight and biomass at *6h* exceeded that at *10h* suggesting overall better growth at *6h*.

Growth was fastest at *3h* with differences between *3h* and the rest of the field reaching a maximum at 61 DAS, after which differences declined. The fastest rate of decline occurred at *3h* after 61 DAS with L being maintained for longer in the less sheltered areas of the field. Although stem elongation and panicle emergence occurred first at *3h* by 85 DAS biomass differences were small relative to *6h* and *10h*, and even smaller differences were found by the time of final harvest. Millet growth at *20h* and control were not significantly different throughout the season suggesting similar growth conditions between the control and the centre of the sheltered field.

2.4.1.5 Comparison of years

The early well distributed rains in 1988 allowed a rapid accumulation of biomass (control field = 8.5 t ha^{-1}), whereas late rains in 1989, followed by drought limited vegetative productivity (control field = 3.6 t ha^{-1}). Differences between the years were reflected in plant heights with millet exceeding 3.0 m in 1988 compared to 2.3 m in 1989. Higher SLA occurred near the windbreak in both years, with values for SLA at different growth stages being similar between years. Panicle emergence and maturity occurred a similar number of days after sowing in both years, despite the delayed onset of rains in 1989. This may result from a day-degree requirement, rather than a day-length requirement for phenological development.

In 1989 maximum biomass at the beginning of the season (46 DAS - 1988, 43 DAS - 1989) was 26 % of that in 1988, with mid-season biomass (61 DAS - 1988, 62 DAS - 1989) being 81 %. Trials from 1984 to 1986 (Moustapha, 1986) reported unsheltered millet biomass in 1986 that was slightly lower than 1988, however higher than that in 1989. In 1989 stem elongation did not occur until 55 DAS whereas in 1988 and 1986 (Moustapha, 1986) it occurred at least 10 days earlier.

Early and mid-season L were respectively 83 % and 28 % lower in 1989, than 1988. L in 1988 was similar to that in 1986 (656 mm rain), with 1989 comparable to 1984 (260 mm rain; Moustapha, 1986). Sadoré locale may produce 30 % more leaf area and 40 % more dry weight than C.I.V.T. (Moustapha, 1986), the variety more often used for field trials (Wallace *et al.*, 1990).

2.4.2 Final Harvest

2.4.2.1 Results 1988

Grain and 1000 grain weight : Grain weight was significantly higher in the control field than at all distances, apart from 3*h*, in the windbreak field (Figure 2.10b), yielding 1.4 t ha^{-1}. Yield at 3*h*, 10*h* and 1*h* were 65 %, 53 %, and 30 % of control grain yield. Average 1000 grain weight was significantly higher on the control (9.7 g) than on the windbreak field (8.6 g).

Number of full panicles and grain weight per panicle : The number of panicles per hectare at 3*h* and control were higher than at 1*h*, 6*h* and 10*h* (Figure 2.10b). The weight of grain per panicle was also significantly higher in the control, resulting in higher grain weight on the control compared to 3*h*. Weight per panicle at 3*h* was significantly higher than 1*h*, however, similar to 6*h* and 10*h*.

Panicle and stover weight : Highest panicle weights were in the control 2.3 t ha^{-1} (Figure 2.10a), with panicle weight at 3*h*, 6*h*, 10*h* and 1*h* being 29 %, 34 %, 34 % and 60 % lower, respectively. Stover weight at 3*h* was larger than control, with

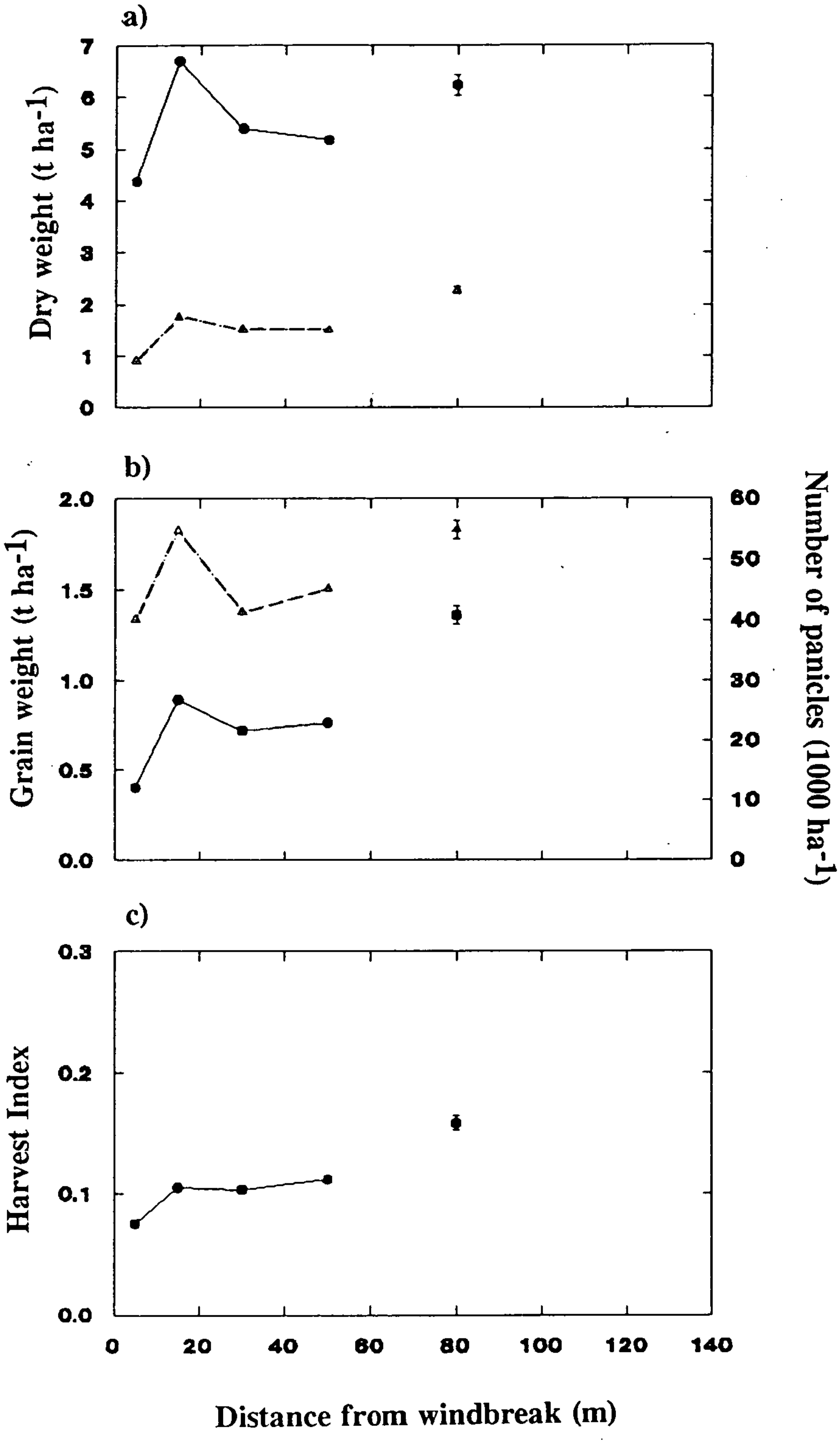


Figure 2.10 Final harvest 1988 a) panicles (△) and stover (●) weights, b) grain weight (●) and number of panicles per ha. (△) and c) harvest index. Unattached point indicates value on control field, error bars indicate ± 1 s.e., (*n* = 6).

weights at 6*h* and 10*h* being similar (Figure 2.10a). As with panicles, significantly less stover was found at 1*h*. Similar values of biomass were found in control and 3*h*, both significantly larger in terms of biomass than 1*h*. Total biomass at 6*h* and 10*h* were 81 % and 79 %, respectively, of control weight (8.5 t ha^{-1}).

Harvest Index : Average harvest index of the sheltered field, excluding 1*h*, was 0.11, (Figure 2.10c). The control had a significantly higher value of 0.16 and 1*h* a lower value of 0.08.

2.4.2.2 Results 1989

Data concerning the eastern and western sides of the windbreak will be referred to as 'E' and 'W', respectively.

Grain and 1000 grain weight : Grain weight near the windbreak was significantly smaller up to a distance of 1*h* from the windbreak compared to grain weights between 2*h* to 8*h* (Figure 2.11b). Grain weight also decreased significantly towards 15*h* to 20*h*. No significant differences were found between the grain weights of 'E' and 'W'. 1000 grain weight increased towards 6*h* attaining similar values to those found on the control and 'W', but decreased towards the centre of the field. None of the differences between 'E' and 'W' were significant.

Number of full panicles and grain weight per panicle : 'E' had significantly higher numbers of panicles per hectare than 'W', with both sides of the windbreak having higher numbers of panicles than the control (Figure 2.11b). Within the windbreak field, millet at 0.5*h* had significantly lower numbers of full panicles than millet between 2*h* and 8*h*.

Grain weight per panicle of the control was significantly higher than that in the centre of the sheltered field (20*h*) and near to the windbreak, and was higher than most of 'E'. Mean grain weight per panicle for 'E' was 20 g compared to 26 g for the control and 23 g for 'W'.

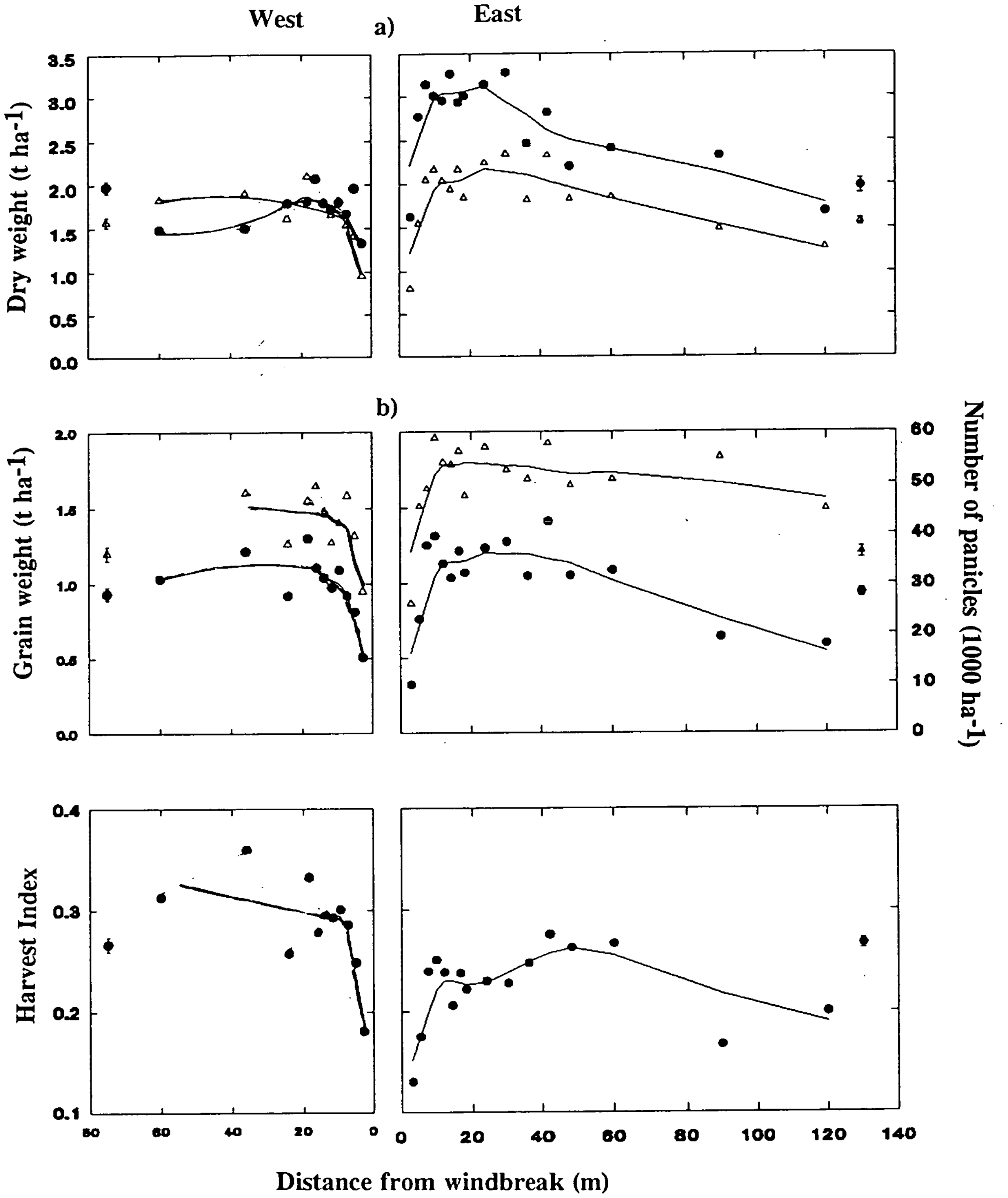


Figure 2.11 Final harvest 1989 a) panicles (△) and stover (●) weights, b) grain weight (●) and number of panicles per ha. (△) and c) harvest index. Lines are moving averages of using 50 % of the values. Unattached point indicates value on control field, error bars indicate ± 1 s.e., (n = 5).

Panicle and stover weight : Significant decreases in panicle weight were measured near the windbreak, in the centre of the field and in the control relative to the 2*h* to 8*h* zone (Figure 2.11a). Higher panicle weights were observed on 'E' than 'W'. Stover yield was significantly (0.1 %) higher on 'E' as compared to 'W' and the control (Figure 2.11a). Yield reductions near the windbreak and in the centre of the field were significantly lower, around 1.5 t ha^{-1}, compared to the 2*h* to 8*h* yield plateau.

Significantly higher total biomass reflected greater stover yield and slightly higher panicle weight found on 'E' (5.6 t ha^{-1}) (Figure 2.11a) compared to 'W' and control (3.6 t ha^{-1}). Substantially lower biomass was found up to 1*h*.

Harvest index : Harvest index (HI) was significantly (0.1 %) lower on 'E' compared to 'W' (Figure 2.11c) resulting from similar grain weights and different biomass. The mean HI was 0.22, 0.28 and 0.27, for 'E', 'W' and control, respectively. HI was below or equal to 0.2 near the windbreaks and in the centre of the field.

2.4.2.3 Summary 1988

Grain yield on the control field (1.4 t ha^{-1}) was larger than average grain yield on the windbreak field, resulting from larger panicles with larger grains rather than more panicles. This suggests that the advantage for growth on the control field came later in the season, i.e. grain filling, rather than during vegetative growth. Lower grain yields on the windbreak field partly resulted from early maturity of panicles and consequent bird and insect damage.

Higher stover weight at 3*h* and higher panicle weight on the control meant that 3*h* and the control had similar biomass, suggesting no advantage of shelter in terms of final harvest biomass, although differences were noted mid-season (Section 2.4.1.3). Differences between 3*h* and 6*h* to 10*h*, were much larger for stover than panicle and grain yield. Increased grain yield at 3*h* resulted from more panicles per hectare. Grain weight per panicle remained constant between 3*h* to 10*h*, with 1000 grain weight decreasing at 3*h*. This supports the idea that shelter is of more benefit in the vegetative growth stages than the reproductive stages. Lower yields of grain and stover were measured at *1h*, resulting from competition. Harvest index was higher on the control field (0.16) than the windbreak field (0.10).

2.4.2.4 Summary 1989

Similar growth was observed at the centre of the windbreak field (*20h*) and the control during sequential harvesting, however at final harvest control grain yield was higher. This may have resulted from the panicles in the centre of the field not being mature at the time of harvest (the control field was harvested 10 days after the windbreak fields, since it matured later). Yield depressions on either side of the windbreak were similar suggesting no difference in the competition between 'E' and 'W' to a distance of 10 m.

Grain weights on the two sides of the windbreak were similar, however 'E' had more panicles and lower grain weight per panicle: 1000 grain weight was slightly higher on the control and 'W', as compared with 'E'. Stover weight and biomass on 'E' was substantially larger than on both 'W' and the control, leading to a higher harvest index on 'W' and control compared to 'E', again suggesting advantages of shelter primarily in terms of vegetative growth.

2.4.2.5 Discussion of both years

Yield decreases in 1989 did not extend beyond 10 m (1.7*h*) from the windbreak, when compared to *3h*, and beyond 5.5 m (*1h*) when compared to *20h*. Yields at *1h* were 62 % and 80 % of biomass and 45 % and 62 % of grain yields at *3h* in 1988 and *4h* in 1989, respectively. Reported yield decreases near to windbreaks extend to distances of *1h* for a variety of crops (Read, 1964) and to 1.6*h* for oats (Kort, 1988). The degree of yield reduction depends upon the tree species, crop species and environment and is discussed at greater length in Chapter 7.

In 1988 maximum sheltered grain and biomass yields were 66 % and 99 % of the control site, in 1989 they increased to 130 % and 145 %. Maximum millet grain yields at *4h* of 121 % were observed for a 10 m high 10 row *Eucalyptus camuldulensis* windbreak in northern Nigeria (Ujah and Adeyo, 1984). A grain yield plateau of 125 % was found between *2h* to *6h*, behind a double row, neem windbreak in the Maggia valley region of Niger (Long and Persaud, 1988). The study in the Maggia valley also suggested that shelter increased biomass more than grain weight, agreeing with the results found here and found for wheat (Vora *et al.*, 1982; see Section 2.1.3).

Sheltered and unsheltered yields were compared by weighting the yield at a particular distance by the area that it represents and allowing for the area taken up by the windbreak and not planted (ca. 7 m^2 per m windbreak, Section 6.3.4). Table 2.8, presents the mean as percentage of the control and 20*h* on the windbreak field, allowing a comparison between controls within and outside the windbreak system. The estimates are calculated on the basis of windbreaks spaced at 60 m and 150 m apart, chosen because measurements of crop yield were taken up to 50 m in 1988 and 120 m in 1989. They also represent the effect of spacing the windbreaks at approximately 10*h* and 20*h*. Calculations are made on the basis of a windbreak at one end, which is slightly different from having windbreaks at both ends of the field (see Section 7.3.2).

Table 2.8 Percentage millet yield for windbreaks at 60 m and 150 m spacing relative to an unsheltered field (control) and 20*h*.

Year (compared to)	Biomass		Grain	
Field length	60 m	150 m	60 m	150 m
1988 (control)	78 %		52 %	
1989 (control)	132 %	101 %	114 %	101 %
1989 (20*h*)	151 %	120 %	180 %	132 %

From this table it is possible to see that in 1988 there was no advantage of shelter for crop production, whereas in 1989 there was. Increases in yield in 1989 were larger when measured over 10*h* than over 20*h* and when compared to a reference within the windbreak site. The reasons for this are discussed in detail in Chapters 5 and 7.

2.4.3 Final harvest 'Density'

2.4.3.1 Results 1988

Treatments were: 'C' for windbreak alone, 'S' for the windbreak supplemented with woven millet barriers; 'E' for eastern side of the windbreak, and 'W' for western side of the windbreak. Decrease in grain weight near the windbreak occurred in all treatments apart from 'CE' (Figure 2.12a). The peak noted at 3*h* in the 'CW' treatment was biased by the proximity of the sample to an ant hill substantially increasing the yield; ignoring this point results in similar growth responses for 'E' and 'W'. The 1000 grain weight remained constant with distance, 'W' having slightly larger 1000 grain weight (8.6 g) compared to 'E' (7.6 g). Panicle weight and biomass had similar patterns to grain and stover weights (Figure 2.12a and 2.12b), with similar responses of 'SE' and 'SW'. Different responses for 'CW' and 'CE' resulted from low number of panicles at 3*h* 'CE' and the high number of panicles at the 3*h* 'CW'. Grain weight per panicle did not change with distance, however average grain weight per panicle for 'E' (13.8 g) was lower than 'W' (16.4 g).

There was on average 0.4 t ha^{-1} more stover on 'E' than 'W', with little difference in biomass. The HI (Figure 2.12c) on 'W' was consistently higher (0.19) than 'E' (0.13), although there were no significant differences between the treatments.

2.4.3.2 Results 1989

Grain weight response to distance from the windbreak (Figure 2.13a) was similar to that observed on 'Standard', lower near the windbreak and towards the centre of the field. Yields formed a plateau on 'E' from 2*h* to 8*h* (maximum yield 0.8 t ha^{-1}), slightly lower than the yield plateau on 'W'. There was no effect of windbreak porosity on the grain yield. Panicle weight followed a similar pattern to grain weight although the decrease in yield towards the centre of the field was smaller. Decreases in grain weight towards the centre of the field resulted from lower grain weight per panicle rather than from fewer panicles.

Stover weight (Figure 2.13b) was low near the windbreak increasing to a yield

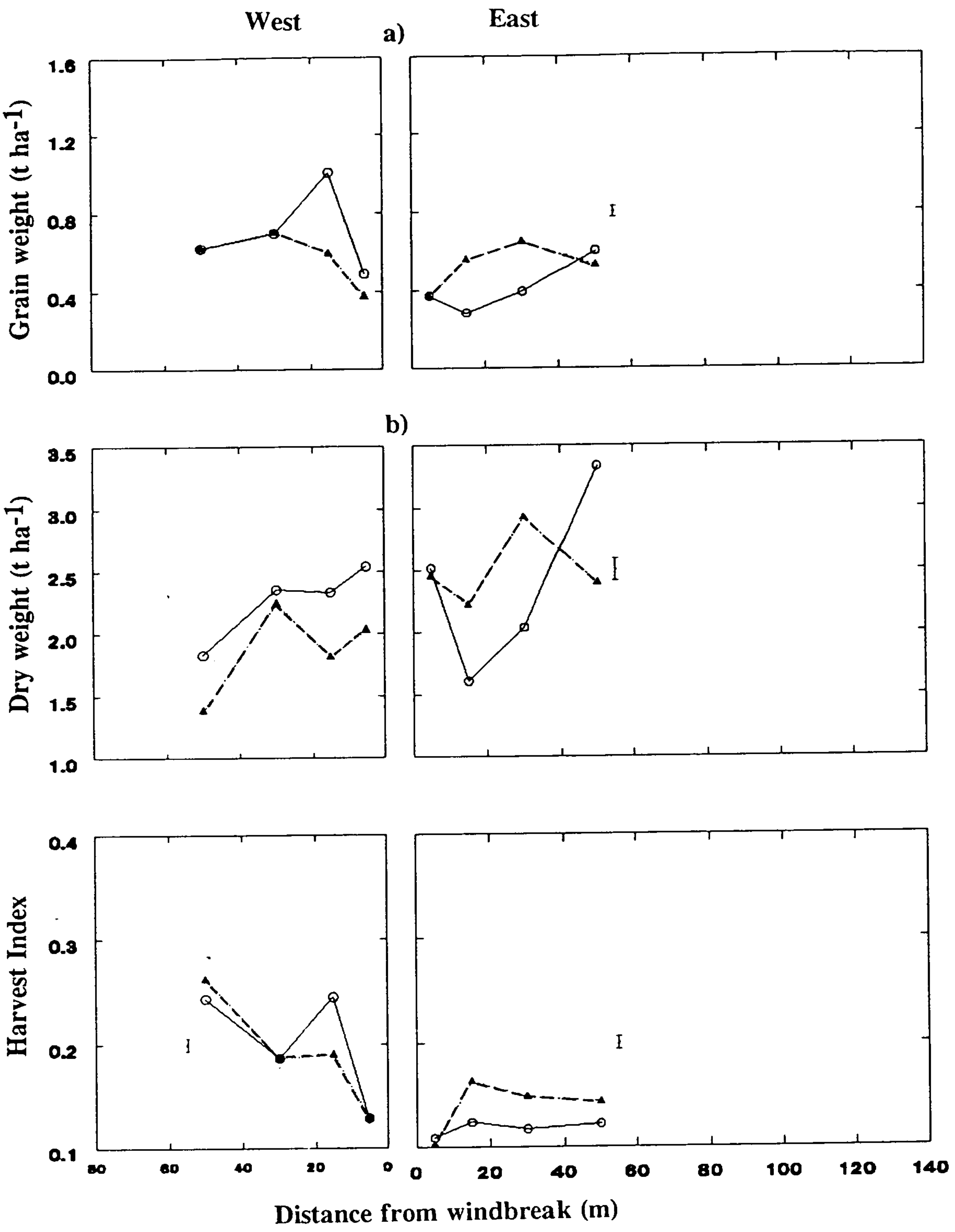


Figure 2.12 Final harvest 'Density' 1988 with millet barrier (▲), and without millet barrier (o), a) grain weight, b) stover weight c) Harvest index. Error bars indicate ± 1 s.e., (*n* = 6).

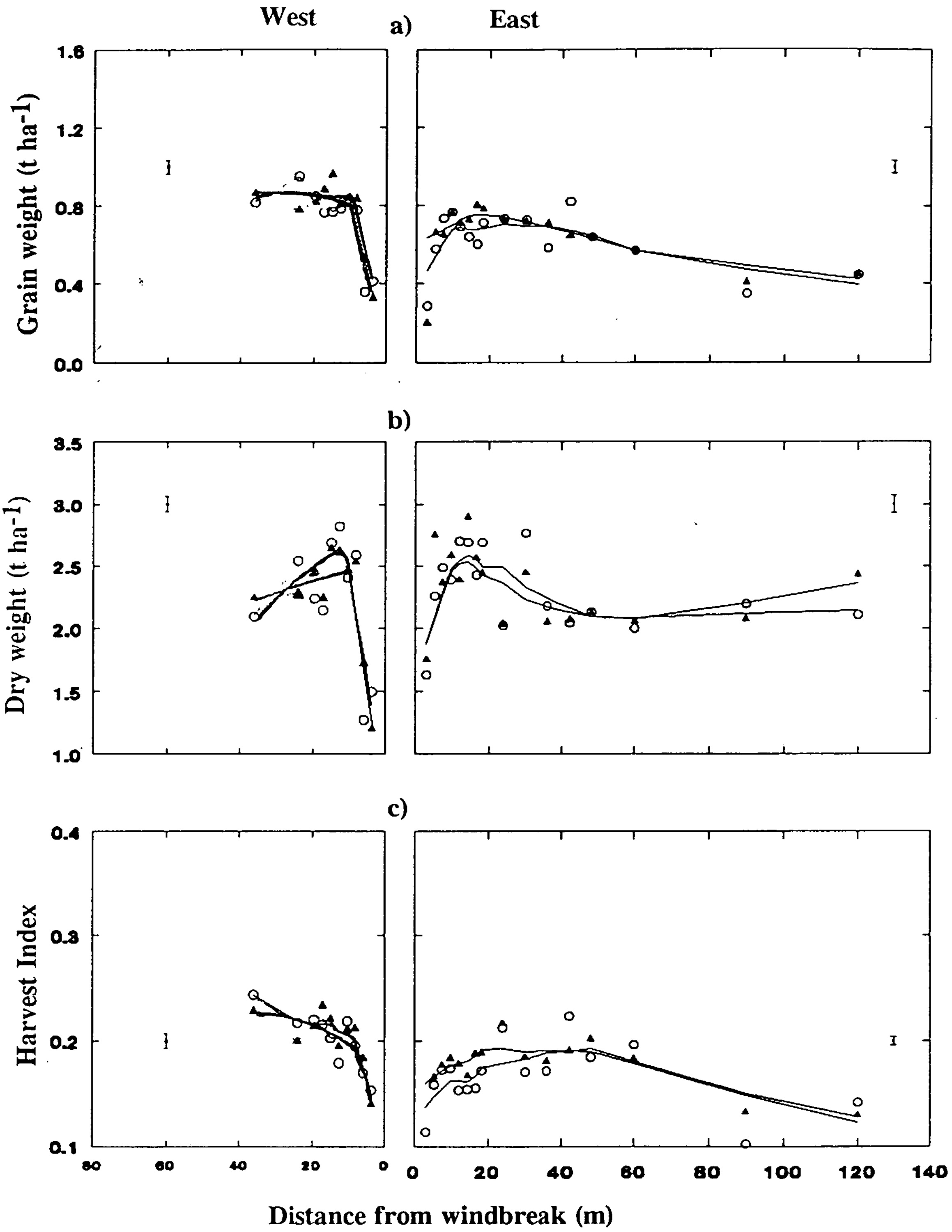


Figure 2.13 Final harvest 'Density' 1989 with millet barrier (▲), and without millet barrier (○), a) grain weight, b) stover weight c) Harvest index. Lines are moving averages using 50 % of the values, error bars indicate ± 1 s.e., (*n* = 4).

plateau 2*h* to 8*h* on 'E' and decreasing towards the centre of the field. Average stover weight on 'E' was 0.2 t ha^{-1} more than 'W', with a similar pattern of total biomass. Slightly higher biomass of 'E' coupled with its slightly lower grain weight gave a higher HI on 'W' than 'E' (Figure 2.13c).

2.4.3.3 Discussion both years

No definite conclusions can be drawn from the 1988 data resulting from insufficient sampling and replication, and extreme variability in the field. The field's low fertility was indicated by grain yields of 0.56 t ha^{-1} compared to field 4d of 1.12 t ha^{-1}, this suggested that nutrients influenced yields more than microclimate (e.g. the influence of an ant hill at 3*h* 'CW'). The effects of treatment were insignificant at final harvest, although differences may have existed during the season.

Differences in HI between 'E' and 'W' resulted from a larger biomass and smaller grain yield on 'E' which occurred in both years. Higher 1000 grain weight and grain weights per panicle on 'W' suggested an advantage at the grain filling stage, supporting the trends of the 'Standard' trial.

Most work on windbreak porosity has concentrated on aerodynamic aspects rather than crop responses (Skidmore and Hagen, 1970). Although wind speeds showed a marked difference between windbreak porosities (Figure 4.9), final yields were unaffected. Changes of crop response to changes in windbreak porosity are not widely reported, '*few studies have compared yield increases for shelterbelts of differing porosities*' (Kort, 1988). Stoeckler (1962) in Nebraska showed decreasing windbreak porosities from 0.48 to 0.14 increased corn yields above control field yields from 2.6 % to 19 %. Jensen (1954) found yields increased 4.3 % and 7 % above the control with slat fences of porosities 0.63 and 0.32. The change of average porosity in this experiment was from 0.27 to 0.05.

2.5 SUMMARY OF RESULTS

1) Millet growth was suppressed throughout the season to a distance of about 1.7*h* on either side of the windbreak, with the largest effect at the start of the season.

2) Fastest mid-season growth was at 3*h* in both years

3) The higher biomass and leaf area index compared to the rest of the field measured at 3*h* at panicle emergence had decreased by final harvest. Leaf area increased and decreased fastest at 3*h*.

4) In 1989 slower early season growth and delayed development was observed at 6*h*.

5) The slowest leaf area increase and decrease was measured in the centre of the field.

6) Grain yields were reduced in shelter in 1988 because early maturity increased bird, insect and disease damage to the millet panicles and the slower growing millet on the control was not short of water because rains were well distributed. In 1989 grain yields were increased in shelter.

7) Shelter increased biomass more than grain, reducing sheltered harvest index.

9) Changing the porosity of the windbreaks, showed no significant changes in yield at final harvest.

CHAPTER 3

INSTRUMENTATION FOR MICROMETEOROLOGICAL MEASUREMENTS

3.1 INTRODUCTION

Many assumptions required for conventional micrometeorological analysis of wind profiles and fluxes, eg. logarithmic wind profiles and large fetches, may not be valid behind windbreaks. Transpiration from a leaf is dependent on its energy balance (eq 1.1) which on a leaf scale requires no assumptions about the fetch or transfer characteristics of the crop. However, it is dependent on the assumption that advection is not significant. Advective effects are important when the internal boundary layer has not fully adjusted (Baldocchi *et al.*, 1988). Advection would be significant if there was a change of vegetation surface, and the height of measurement was outside the boundary layer characteristic of the surface of interest.

Measurements taken during this project aimed to reduce advective errors by positioning instruments near the leaf surface and 200 m down-wind of a millet field. In this analysis the micrometeorological effects of windbreaks were investigated at: (i) a leaf scale (leaf surface - air at crop height), and (ii) a crop scale (air at crop height - reference height above the crop). The components of the leaf energy balance (eq 1.2b) for millet leaves at a series of distances from the windbreak were measured, together with the soil heat flux.

Measurements of leaf and air temperatures give the gradient for sensible heat transfer from leaf to air. Stomatal cavity water vapour pressure and air water vapour pressure give the gradient for water vapour transfer. Stomatal conductance and leaf boundary layer conductance are also needed to calculate fluxes of water and sensible heat. The sum of these two fluxes should equal the net radiation absorbed by the leaf, assuming that other energy sinks and sources in the leaf are small (Section 1.3.2.2).

The following section describes the design and calibration of each instrument used for the measurements mentioned above. This is followed by a section outlining the layout of the instruments in the field, including a test of the spatial variability of the plant-based measurements in the field.

3.2 INSTRUMENTATION

3.2.1 Net radiation

The net radiometers used in 1988, included two linear net radiometers, (21", Swissteco Pty Ltd., Melbourne, Vic. Australia), one single dome hemispherical net radiometer (Swissteco) and one double dome hemispherical net radiometer (Q4, REBS, Seattle, Washington, USA). In 1989 three Q4s were used. Good agreement was found when these were checked against each other over bare soil at the beginning of the season.

Outer domes of the net radiometers were abraded by severe sandstorms and degraded after prolonged exposure to ultra-violet light, so were replaced every 2 to 3 months over the season. Double dome Q4 net radiometers have recently been shown to be inaccurate (Oliver and Wright, 1990), however measurements can be corrected, if net solar radiation (S_n) is known, using the equation (3.1):

$$(R_n)_a = 1.67(R_n)_d - 0.67S_n \tag{3.1}$$

Where $(R_n)_a$ is actual net radiation, $(R_n)_d$ is net radiation measured with the Q4 net radiometer, where S_n is given by equation (3.2):

$$S_n = S_t(1 - \alpha). \tag{3.2}$$

Where S_t is incoming solar radiation and α is reflectance of solar radiation of the underlying surface. Since α changes with vegetation cover the value has been weighted using eq. 3.3, where S_i is solar radiation intercepted by the millet crop, α_m is reflectance of solar radiation by millet and α_s is reflectance of solar radiation by dry soil:

$$\alpha = (\alpha_m (S_i / S_t)) + \alpha_s(1 - (S_i / S_t)) \qquad (3.3)$$

The fraction of solar radiation intercepted is dependent on leaf area index L and the radiation extinction coefficient of the crop, K:

$$(S_i/S_t) = (1 - e^{-KL}) \qquad (3.4)$$

Values of 0.25 and 0.35 were taken as α of millet and dry sand, respectively (see Section 5.2.1.1) and extinction coefficient of daily solar radiation as 0.43 (Wallace *et al.*, 1989). Daily average values of L were calculated from millet growth data presented in Chapter 2. All values of net radiation were corrected using equation 3.1, reducing day time values by ca. 30 W m^{-2}.

3.2.2 Ground heat flux

Heat flux plates designed and constructed at Edinburgh University consisted of an 8 cm x 2 cm plastic former 2 mm thick on which was wound approximately 100 turns of 0.27 mm diameter constantan wire. The plate was half insulated with nail polish then electroplated with copper in a bath of copper sulphate. The plate was encapsulated in a high thermal conductivity resin (RS no. 552-668, RS Components, Corby, UK), giving it a similar thermal conductivity to dry sand (Kimball and Jackson, 1979). Large differences between the conductivity of soil and plate may cause errors by preferential heat flow through the more conductive media.

Plates were calibrated in an insulated, sand-filled box equipped with a heating element at the bottom. A series of thermocouples at different depths measured the temperature gradient in the box. Output from each heat flux plate was measured over a range of power inputs and consequent temperature gradients, and flux of heat passing through the plate was calculated from the power input and checked using the slope of the temperature gradient (Kimball and Jackson, 1979). Plates were also tested against a factory calibrated heat flux plate (HFT-1, REBS, Seattle, WA, USA), in a dry sand in Niger. The Edinburgh plates showed slight hysteresis

(Figure 3.1) when compared to the REBS plate, probably as a result of the higher thermal mass of the Edinburgh plate.

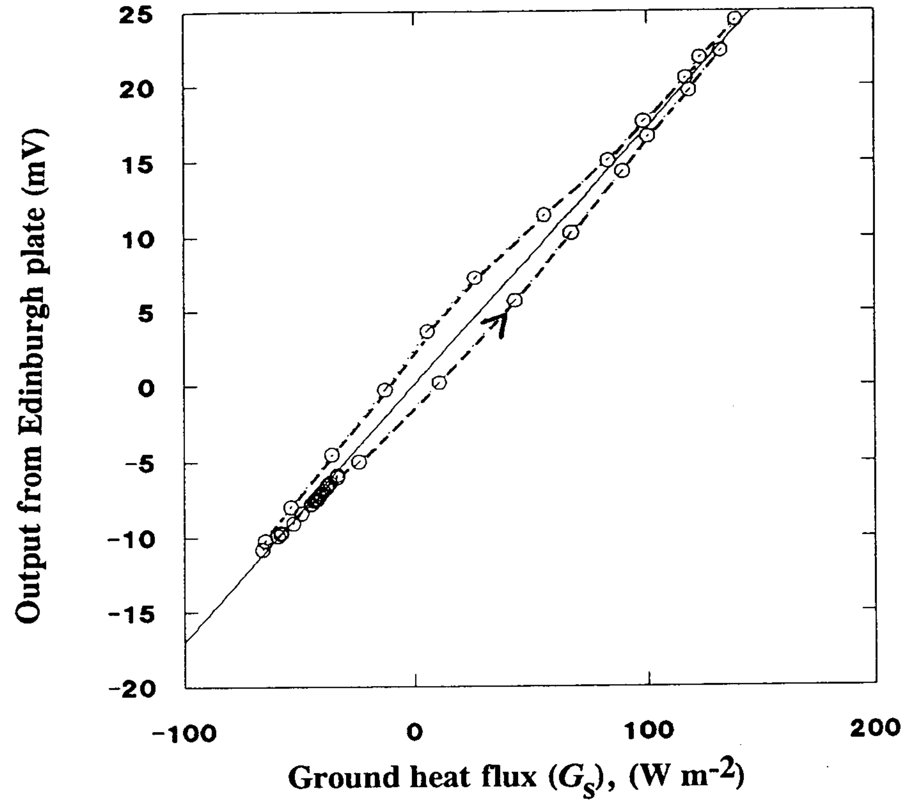


Figure 3.1 Voltage output from an Edinburgh heat flux plate compared with G_S measured with a REBS plate, over the course of a day. Installed at 5 mm depth in a dry sandy soil in Niger.

3.2.3 Solar radiation

S_t was measured using a hemispherical solarimeter (CM3, Kipp & Zonen Inc, Delft), mounted over a fallow bush site, approximately 1 km from the windbreak. These data were provided by the Institute of Hydrology, Wallingford.

One metre long tube solarimeters constructed at the ICRISAT Centre, Hyderabad, India (Green and Deuchar, 1985) were used to measure solar radiation interception by the tree canopy. These were calibrated against a hemispherical solarimeter in the same orientation as used for the measurements of transmissivity of solar radiation.

3.2.4 Humidity

The psychrometers used to measure air temperature and humidity were ventilated low cost psychrometers built at Edinburgh University. Design and calibration are described in detail in Appendix III.

Some data for refernce humidities were provided by the Institute of Hydrology, from their fallow bush site.

3.2.5 Wind speed

Cup anemometers were used for measurement of horizontal wind speed (Met One, Grants Pass, Oregon, USA), (A100, Vector Instruments, Rhyll, UK). Starting speeds of the Met One and the Vector cup anemometers were 0.45 m s^{-1} and 0.25 m s^{-1}, respectively. Anemometers were regularly checked and all bearings replaced before each new season of measurements. Agreement of within 3 % between the two type of anemometers was found for wind speeds below 3 m s^{-1}, decreasing to 8 % for wind speeds above 5 m s^{-1}.

3.2.6 Wind direction

A potentiometric wind vane (W200P, Vector Instruments, Rhyl, UK) was used to measure wind direction. It was mounted at a height of 5 m on the western side of the windbreak. Bearings given by the wind vane were checked using a hand held compass.

3.2.7 Boundary layer conductance

Heated leaf replicas were designed and constructed at Edinburgh University and are explained in detail in Appendix IV. It was necessary to use heated leaf replicas to complement horizontal wind speed measurements, so as to take account of wake turbulence effects behind the windbreak, since transfer of heat and water vapour to and from leaves is dependent on both vertical and horizontal wind speed components. The shape of the leaf affects energy transfer (Dixon, 1982), so the replica was based on a fully developed millet leaf.

3.2.8 Stomatal conductance

Stomatal conductance of leaves was measured using a null balance porometer (LI1600, LI-COR Inc., Lincoln, Nebraska, USA). The 2 cm^2 circular aperture cuvette was used for all measurements on millet leaves. Measurements were taken on both upper and lower surfaces of undamaged leaves. Measurements of quantum flux density, humidity and leaf temperature were recorded simultaneously.

The conductances from the porometer were verified using the micropipette supplied by the manufacturer that allowed measurement of evaporation from wetted blotting paper within the cuvette, for comparison with that calculated by the porometer. Agreement between methods was ± 10 %.

3.2.9 Leaf temperatures

Leaf temperatures were measured using copper-constantan, 0.27 mm diameter (type T) thermocouples (76P, Comark Electronics Ltd., Rustington, U.K.), attached to the underside of the leaves using plastic paper clips. Wires were attached so as to ensure that at least 5 cm of the thermocouple wire was in the leaf boundary layer to reduce errors from heat conduction. Adhesive was not used in order to prevent blocking of stomata and localised reduction of transpiration, that may lead to hot spots being sensed by the thermojunction. A test was carried out to check thermal contact of thermocouple to leaf using a heat-sink compound (RS no. 554-311, RS Components, Corby, UK). This test failed to show any systematic differences between heat-sink-coated, and non-coated thermocouples.

Thermocouples were wired as pairs in parallel, so that one measured value gave an average of two leaf temperatures. In most cases thermojunctions on leaves were referenced to an aluminium block in a junction box. The temperature of this block was measured with a 10 kΩ thermistor (Fenwall Unicurve C-UVA41JI, BFI IBEXA Electronics Ltd., Aylesford, UK). In certain configurations reference thermojunctions of leaf thermocouples were positioned in the psychrometer air stream and referenced against air temperature, measured by the psychrometer. This gave a direct measurement of leaf to air temperature difference, but the wiring made it impractical on a wide scale.

3.2.10 Junction box

In 1989 a series of junction boxes was used to simplify wiring and provide a reference block for thermocouple temperature measurements. The plastic box was 24 cm x 12 cm x 10 cm, with cable glands for incoming cables that connected to 12 core cables via terminal blocks, and a 12-way plug. The box contained a split aluminium block within which the reference copper-constantan thermojunctions were sandwiched.

3.2.11 Logging system

All instruments used were logged on a series of solid state loggers (Campbell Scientific Ltd., Logan, Utah, USA). In 1988 the main logging system was a 21x with two AM32 multiplexing units, allowing one analogue channel to be increased to 32. In 1989 CR10 loggers were used on most configurations, with the 21x being used only for short-term logging. The AM32 and SDM-SW8A switch closure multiplexers were used in 1989 for the multiplexing of the voltage channel and pulse channels, respectively.

Data were retrieved on magnetic tape, and transferred to an IBM PC, where they were processed using Dbase3+, and SYSTAT/SYGRAPH packages.

3.3 DISPOSITION OF INSTRUMENTATION

Over two years a series of configurations of micrometeorological instrumentation were used to: (i) monitor the microclimatic changes resulting from windbreaks and (ii) make more detailed studies on specific aspects of changes in microclimate. The configurations are summarized below and are described in more detail in later sections.

> **Configuration A** - The change of microclimatic variables with distance from the windbreak was measured over the whole cropping season, and

comparisons made with a station on the windward side of the windbreak and in an unsheltered field (Figure 3.2a).

Configuration B - The differences in air and leaf temperatures, humidity, and boundary layer conductance were measured within the millet crop at different distances from the windbreak. This allowed scaling of the point measurements made in configuration A to the whole crop (Figure 3.2b).

Configuration C - The vertical profile of horizontal wind speed was measured at different distances from the windbreak. This allowed determination of the change of the wind profile with distance from the windbreak, and provided information about transfer of momentum from atmosphere to crop (Figure 3.2c).

Configuration D - Horizontal wind speeds were measured over bare soil at heights of 1 m and 3 m behind a windbreak, to determine changes in wind speed with height and distance from the windbreak (Figure 3.2d).

Configuration E - Reduction of solar radiation caused by the windbreak was measured while no crop was present. This provided information on the pattern of shading by the windbreak (Figure 3.2e).

3.3.1 Configuration A

3.3.1.1 Station Positions

Permanent micrometeorological stations were set up at four distances 1*h*, 3*h*, 6*h* and 10*h* on the eastern side of the windbreak in both 1988 and 1989, where *h* is the height of the windbreak (Figure 2.2). Reference stations were set up on the western side of the windbreak at distances of 50 m in 1988 and 36 m in 1989 from the windbreak, and in an unsheltered field 7b2 (Figure 2.1). Station positions are summarized in Table 3.1. All measurements were logged every 20 seconds and averaged over 30 minutes, disposition of the instruments is presented in Figure 3.2a.

CONFIGURATION A

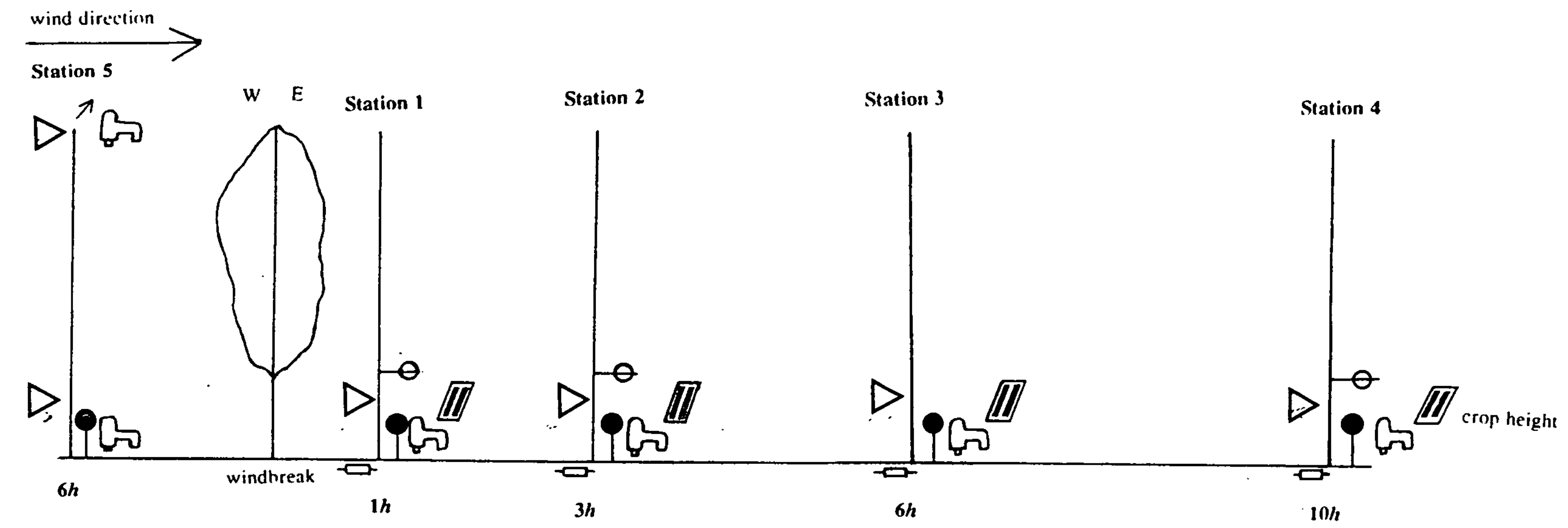


Figure 3.2a Configuration A - Layout of instruments at 5 permanent micrometeorological stations for measurement of the shelter effect of a windbreak. *h* is height of windbreak (6 m in 1989).

CONFIGURATION D

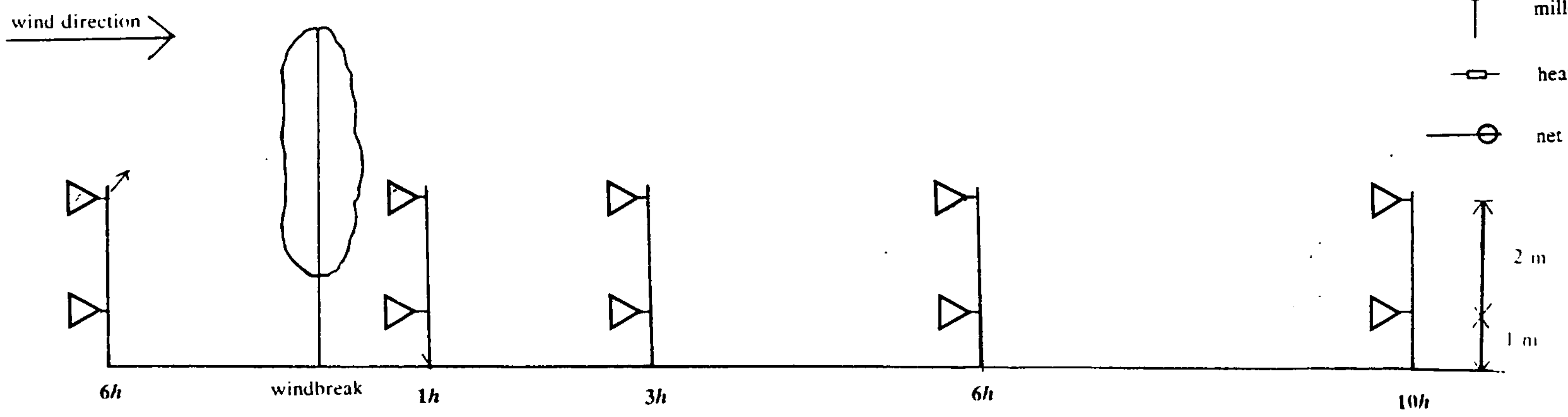
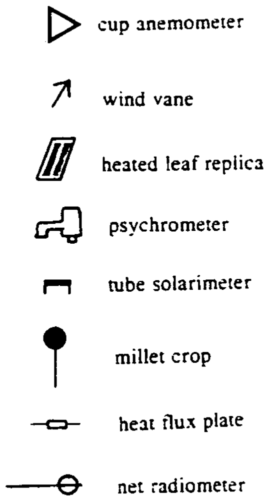


Figure 3.2d Configuration D - An array of cup anemometers to measure the wind speed pattern behind different porosity windbreaks.

SYMBOLS



CONFIGURATION B

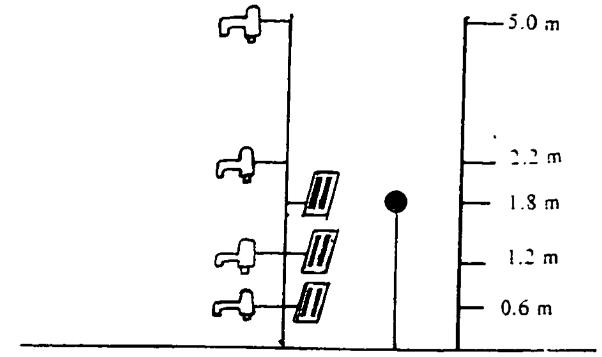


Figure 3.2b Configuration B - A moveable mast for measuring profiles of humidity, air and leaf temperatures, and boundary layer conductance, within the canopy at different distances from the windbreak.

CONFIGURATION C

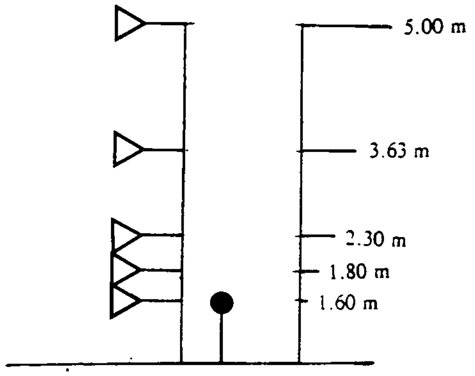


Figure 3.2c Configuration C - A moveable mast for measuring profiles of wind speed at different distances from the windbreak.

CONFIGURATION E

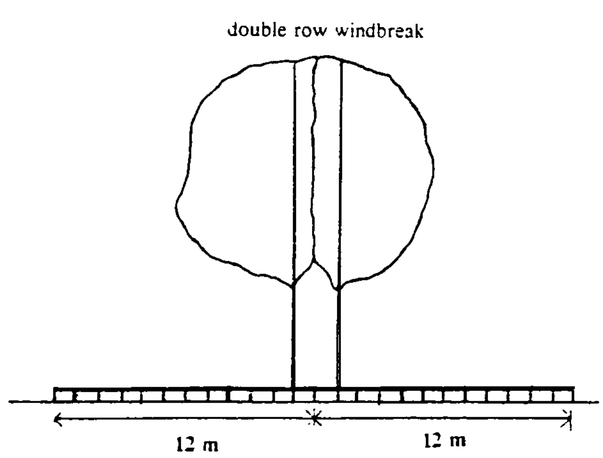


Figure 3.2e Configuration E - An array of tube solarimeters under a double row windbreak to measure the light intercepted by the trees.

Plate 4.1 Layout of the four micrometeorological stations on field 3b, trial 'Standard', Configuration A. Stations were at distances of 1*h*, 3*h*, 6*h* and 10*h* from the windbreak, millet was at around 50 DAS.

Table 3.1 Positions of micrometeorological stations in configuration A for 1988 and 1989. Farm layout shown in Figure 2.1.

		Distance from windbreak		
		1988	1989	Field
Station 1	1*h*	5 m	6 m	3b
Station 2	3*h*	15 m	18 m	3b
Station 3	6*h*	30 m	36 m	3b
Station 4	10*h*	50 m	60 m	3b
Station 5	windward	50 m	36 m	3a
Station 6	unsheltered	-	-	7b2

3.3.1.2 Disposition of instruments at stations

Net radiometers : Net radiometers were installed 10 cm above the canopy in 1988 and 50 cm above the canopy in 1989, being raised during the season with growth of the crop. They were re-randomised during the season to exclude any systematic instrumentation errors. Net radiometers remained throughout the season at stations 1 and 4 in 1989, the third net radiometer being moved between stations 2, 3 and 6.

Psychrometers : Psychrometers were positioned in both years at approximately the height of the zero-plane displacement (d) plus the roughness height (z_0), ie. (z_0 + d), which was approximated to $0.7h_c$ where h_c is crop height. This involved frequent adjustment of the height of the psychrometers in relation to growth of the crop. At the beginning of the season when plants were small, the psychrometers were placed at 40 cm until $0.7h_c$ exceeded this.

Psychrometers were positioned at $0.7h_c$ for all stations and at a reference height of 5 m for stations 5 and 6. At the beginning of the season, in 1989, two psychrometers were run at each station to check variability of the measurements.

Average day-time difference between instruments was ± 0.11 K for air temperature and ± 0.08 kPa for vapour pressure deficit.

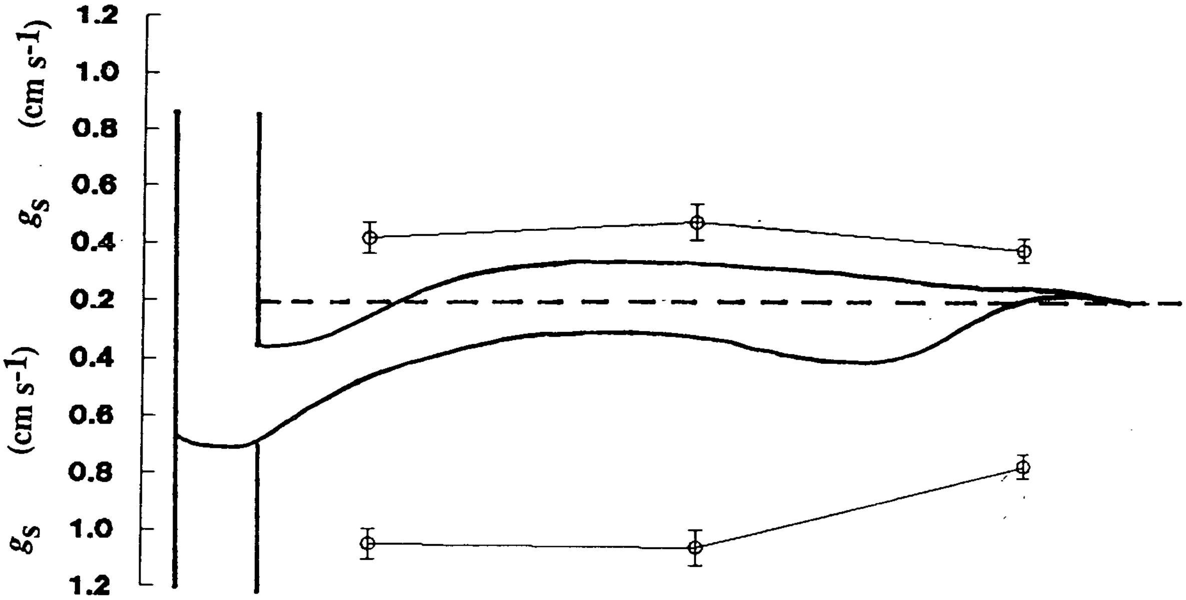
Cup anemometers : Cup anemometers (Met One) were positioned 20 cm above the crop at all stations to avoid interference from millet leaves or panicles. Reference wind speed was measured at a height of 5 m at stations 5 and 6. The anemometers were re-randomised at three week intervals to prevent systematic errors. In 1988, instrumentation limitations allowed wind speed measurements at only station 4 and 5.

Heated leaf replicas : To prevent shading by millet leaves, leaf replicas were placed at the same level as the cup anemometers, approximately 20 cm above the crop. Leaf replicas were installed at stations 1 to 4 and re-randomised at three week intervals over the season to prevent systematic errors.

Porometer : In 1988 measurements were taken to establish the variability of stomatal conductance (g_s) over the leaf and within the millet canopy, measuring three positions on six leaves of three plants (Figure 3.3). Changes of g_s over the day within the canopy are discussed in Section 5.2.5.1. The average conductance of both sides of the leaf was approximately 0.75 cm s^{-1} at the centre and base of the leaf, but was lower (0.58 cm s^{-1}) near the tip of the leaf. These differences were not significant at the 5 % level. Variation of conductance with depth in the canopy was also not significant (Figure 3.4), although maximum g_s was found at leaf 2 to leaf 3, decreasing towards the base of the canopy. Reducing sampling to alternate leaves gave a calculated average stomatal conductance of 0.68 cm s^{-1} as opposed to 0.69 cm s^{-1}, introducing a negligible error.

In 1988 measurements of g_s were made on both upper and lower surfaces of alternate leaves of four plants at stations 1 and 2, every 2 hours (09.00 h - 17.00 h). Early morning measurements (07.00 h) were abandoned because of problems caused by dew on the leaves. To avoid errors from dew-fall, leaves were gently dried with blotting paper one hour before the measurements were taken. Four sets of measurements were taken during the 1988 season, (see Table 3.2).

Figure 3.3 Stomatal conductance (g_S) on adaxial and abaxial leaf surfaces, over a fully expanded millet leaf, 45 DAS, at 13.00 h. Error bars indicate ± 1 s.e., (n = 18).



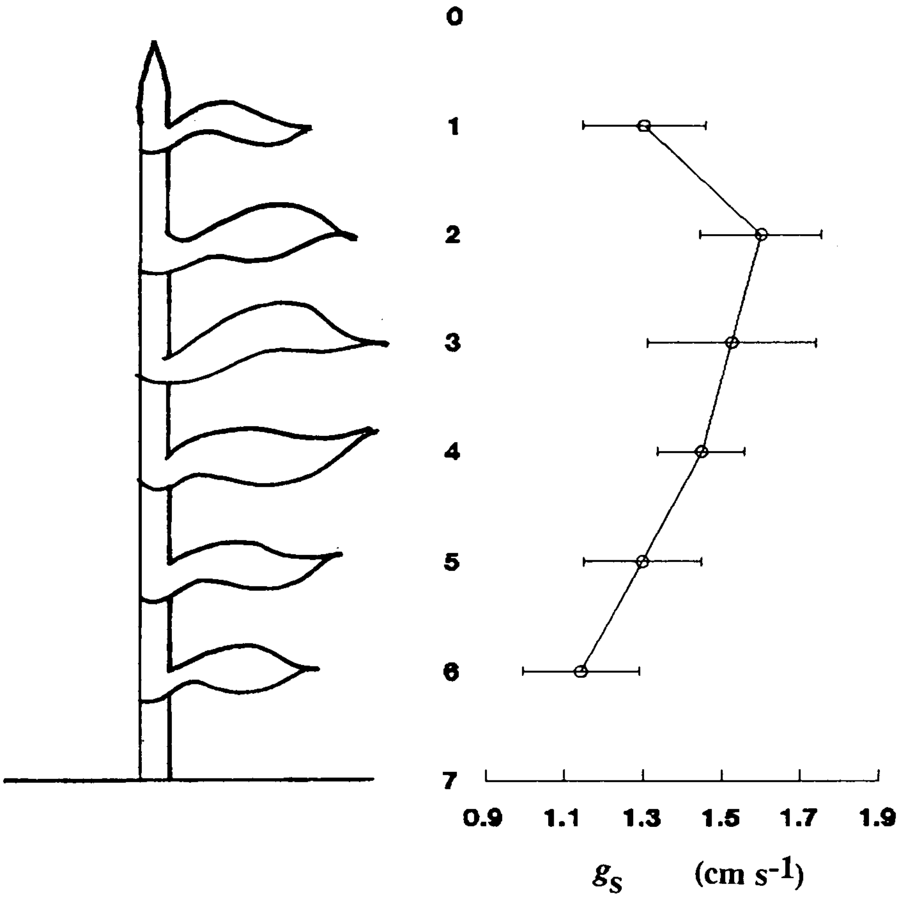


Figure 3.4 Changes of stomatal conductance (g_S) with depth in canopy, taken at 45 DAS at 13.00 h. Error bars indicate ± 1 s.e., (n = 9).

of the effect of distance from the windbreak. In 1989 three plants were measured three times during the day, morning (10.00 h), midday (13.00 h) and afternoon (16.00 h), at stations 1, 2, 3 and 4. Additional measurements of g_s were taken at a distance of 20*h* from the windbreak as a measure of g_s in an unsheltered crop, although there was no micrometeorological station. Measurements were made on both leaf surfaces, at three heights in the canopy. Using data from station 2 and day IV 1988, the change from measuring alternate leaves (5 layers) to a three layer sample in 1989 introduced a maximum error of 0.6 % in mean leaf stomatal conductance. If average daily g_s is calculated from the 09.00 h, 13.00 h and 17.00 h sampling times and compared with an average based on five sampling times during the day, g_s is underestimated by about 8 %. This is probably an overestimate of the error introduced by sampling only three times a day, since in practice the morning sampling period began at 10.00 h and the afternoon period at 16.00 h, as opposed to 09.00 h and 17.00 h, in the five samples a day system.

Table 3.2 Sampling dates for porometry 1988 and 1989

Measurement day	1988 date	DAS	1989 date	DAS
I	20/7/88	39	18/8/89	44
II	3/8/88	53	20/9/89	77
III	17/8/88	67	29/9/89	86
IV	7/9/88	88		

DAS - Days after sowing

Heat flux plates : Four plates were connected in series to give an average for the area between four millet plants, each plate being placed in a different quarter of the area (see Figure 3.5). The plates were installed at 5 mm depth and covered with soil. Although plates sometimes became exposed during heavy rain this depth was preferred to deeper installation, to minimise errors resulting from heat storage in the soil above the plates. Measurements of soil heat flux were made at stations 1, 2, 3, 4 and 6.

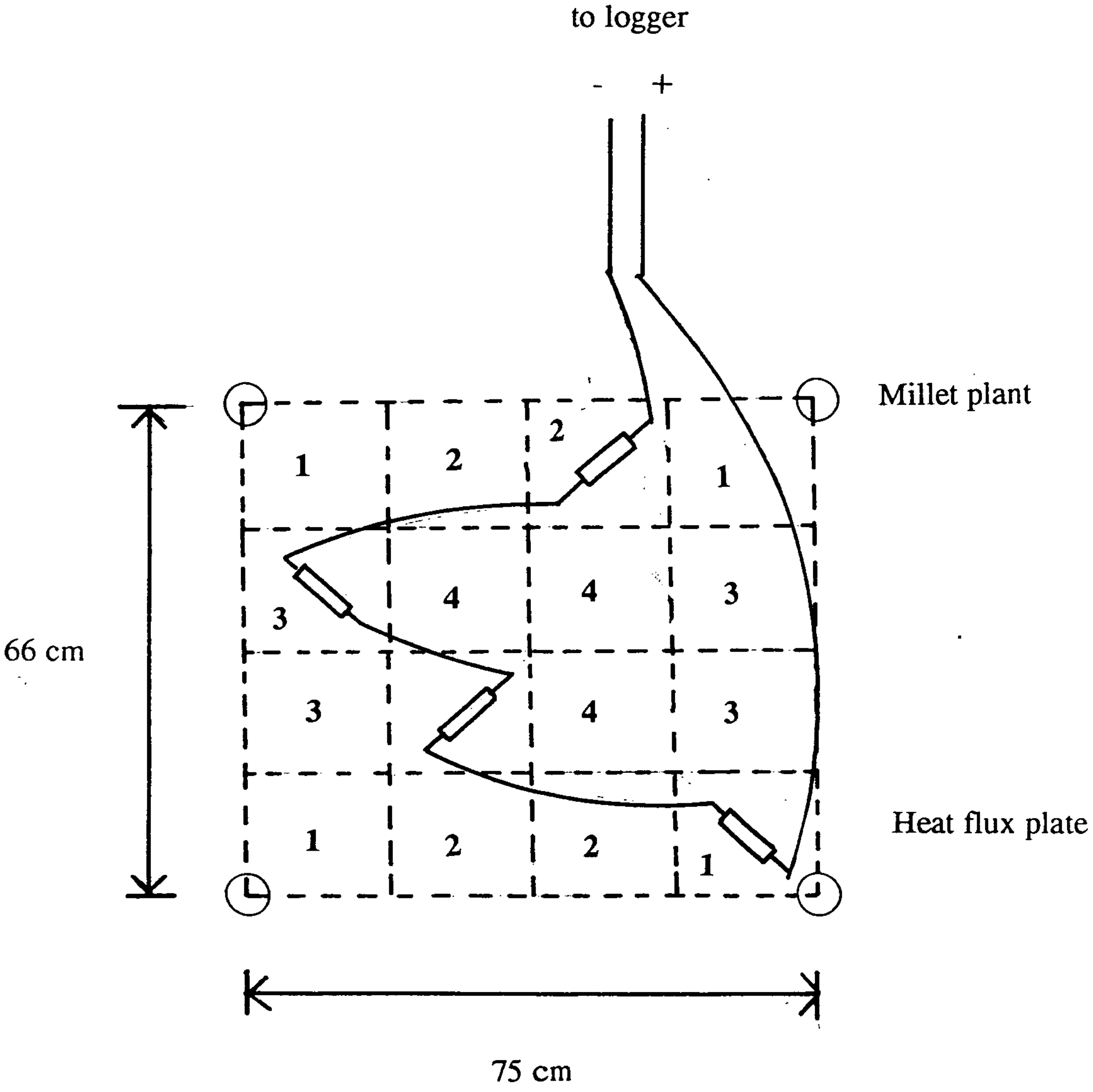


Figure 3.5 Layout of heat flux plates to measure average heat flux between four millet plants. The four quarters of the area between plates were sampled with a plate placed in a randomly selected quadrant, with the restriction that each of the four quadrants 1 - 4 should be sampled.

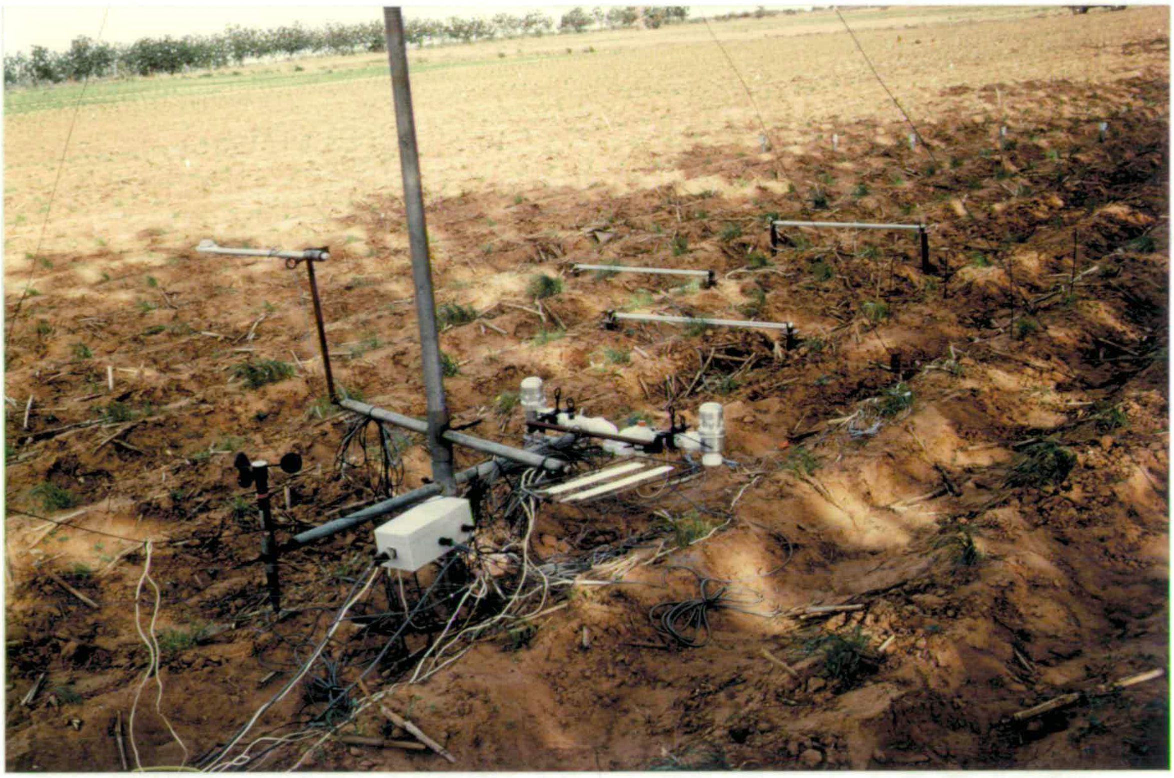


Plate 4.2 Layout of station 1, Configuration A, at the start of the season. Showing two psychrometers, a net radiometer, a cup anenometer, a pair of heated leaf replicas, a junction box, and three tube solarimeters.

Leaf Thermocouples : A preliminary study was carried out in 1988 to examine the gradient of leaf temperature within the crop in unsheltered millet. Measurements of leaf temperature were taken on four alternate leaves of five millet plants over three days. Measurements were taken using leaf thermocouples, (Section 3.2.9), and hourly averages were calculated for each leaf and plant.

Figure 3.6 shows profiles of leaf temperatures for a crop nearing maximum leaf area at times during the day. Maximum temperatures were measured in the top and bottom layers of the canopy. If temperature at the top of the canopy is compared with unweighted average canopy temperature, the largest difference from the average was 0.28 K at 13.00 h. Small temperature gradients within a millet crop were also found by Wright (1990) using an infra-red thermometer.

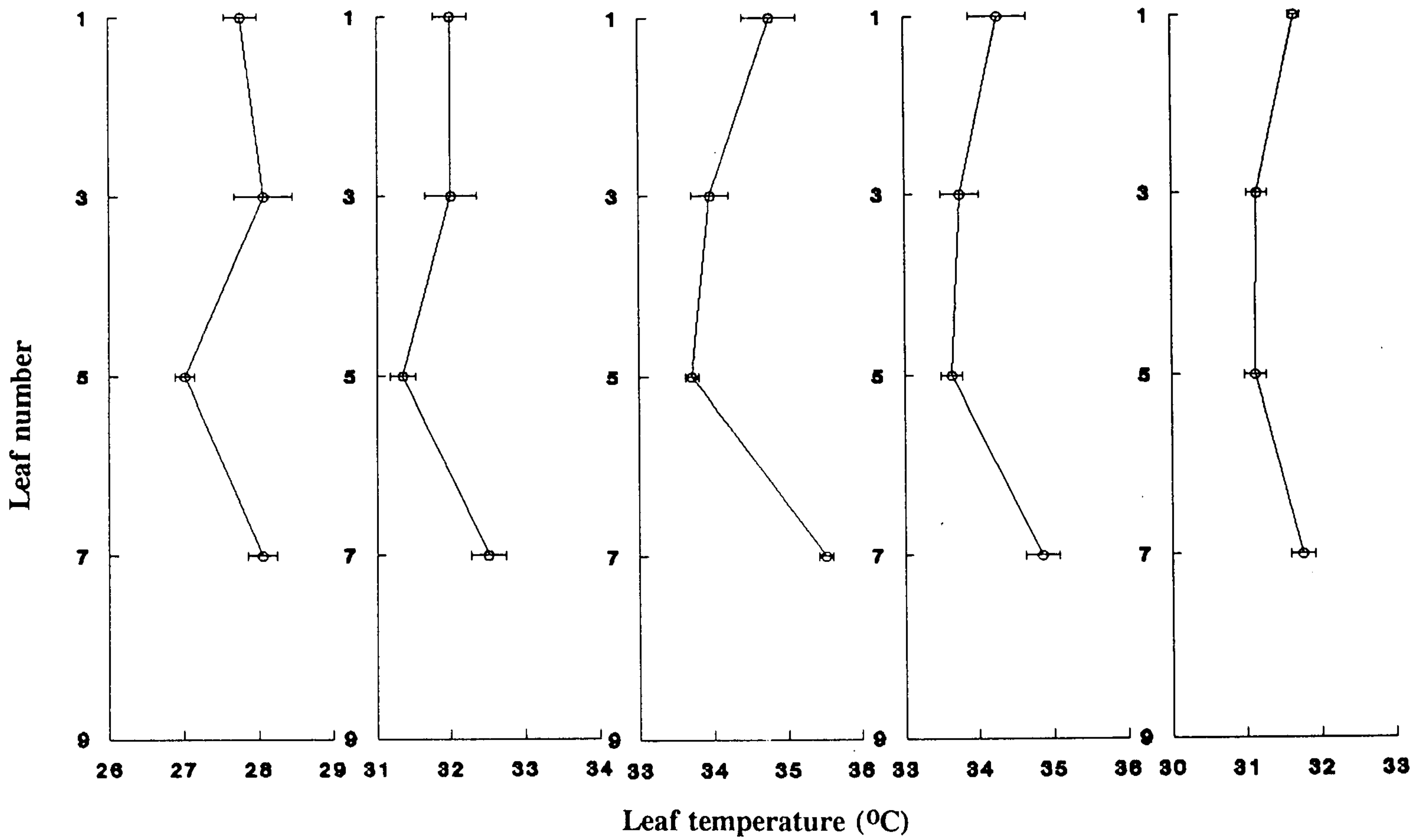


Figure 3.6 Leaf temperature profiles, within a 1.2 m unsheltered millet crop, at a) 09.00 h, b) 11.00 h, c) 13.00 h, d) 15.00 h, and 17.00 h averaged for 3 days during November 1988. Error bars indicate ± 1 s.e., ($n = 5$).

Based on these results thermojunctions connected in parallel were attached to the first and second uppermost fully expanded millet leaves, excluding the flag leaf. There were three replicates at each station, apart from station 5. The leaf thermojunctions were referenced to a thermistor in the junction box.

A summary of instrument deployment for configuration A in 1989 is presented in Table 3.3.

Table 3.3 A summary of instrument deployment for configuration A.

	station					
Measurement	1	2	3	4	5	6
Net radiometer	x	*	*	x	-	*
Psychrometer	x	x	x	x	xx	xx
Leaf thermocouples	x	x	x	x	-	x
Heat flux plates	x	x	x	x	-	x
Cup anemometer	x	x	x	x	xx	xx
Leaf replicas	x	x	x	x	-	-
Porometer	x	x	x	x	-	- @
Wind Vane	-	-	-	-	x	-

x....instrument permanently at that position
*....some of time
xx...also at z = 5 m
@....samples taken at x = 20h

3.3.2 Configuration B

Layout of configuration B is shown in Figure 3.2b. Measurements were started on Julian day 249 1989, at 100 m from the windbreak. The mast was then moved towards the windbreak with between 5 to 7 days spent at stations 4, 3, 2 and 1. Measurements were taken every 10 seconds and averaged over 30 minutes.

Air temperature and humidity were measured at heights of 2.2 m (level with the millet panicles), 1.2 m (level of maximum leaf area), 0.6 m (where some leaves were already undergoing senescence) and at a reference height of 5 m.

Heated leaf replicas were installed at three heights to measure boundary layer conductance and leaf temperatures were measured with leaf thermocouples, referenced to the air temperature of the psychrometer. Changes of position of the configuration are given in Table 3.4.

Table 3.4 Position of configurations B and C with Julian Day

Julian day		Distance from windbreak		
Config B	Config C			Field
	237 - 245	120 m	20*h*	3d
249 - 257	249 - 257	100 m	16.7*h*	3b
257 - 265	257 - 265	60 m	10*h*	3b
265 - 271	265 - 271	36 m	6*h*	3b
271 - 276	271 - 276	18 m	3*h*	3b
276 - 282	276 - 282	6 m	1*h*	3b

3.3.3 Configuration C

This configuration also moved from site to site (Table 3.4), layout shown in Figure 3.2c. Horizontal wind speed was measured with cup anemometers (Vector), at heights of 5 m, 3.63 m, 2.3 m, 1.8 m and 1.6 m. Averages and standard deviations were recorded every hour.

3.3.4 Configuration D

This configuration was set up after the cropping season, once the millet stover was harvested and ploughed in (Figure 3.2d), consisted of cup anemometers set up at heights of 3 m (Met One) and 1 m (Vector), at stations 1, 2, 3, 4 and 5. Wind direction was measured at station 5. Measurements were taken over a two week period between Julian day 341, 1990 to day 9, 1991.

3.3.5 Configuration E

An array of tube solarimeters was arranged perpendicular to the line of the windbreak, after the millet straw had been ploughed in both 1988 and 1989. The solarimeters were lined up end to end covering a distance of 12 m either side of the centre line of the windbreak, (see Figure 3.2e). The line was moved every 4 to 5 days, to allow measurement of transmitted solar radiation under different parts of the windbreak. Nine lines were measured in 1988 and 3 lines in 1989. The measurements were compared with a reference tube solarimeter, mounted 25 m away from the windbreak at a height of 4 m .

CHAPTER 4

EFFECT OF WINDBREAKS ON AIR FLOW

4.1 INTRODUCTION - REVIEW OF THE EFFECTS OF WINDBREAKS IN AIR FLOW

4.1.1 Normalizing wind speed and turbulence

The effect of windbreaks on leeward air flow has been extensively reviewed by Jensen (1954), Caborn (1957), Van Eimern *et al.* (1964) and has been summarized most recently by Heisler and Dewalle (1988) and McNaughton (1988). In the following section, I will not attempt to cover the literature extensively, but will discuss variables that influence the effectiveness of the shelter provided by a windbreak.

Evaluation of windbreak effectiveness depends on the purpose for which the windbreak was established. Effectiveness will be discussed here in terms of wind speed and turbulence. Most studies of wind flow over windbreaks of both slat fences and living trees led to the conclusion that the distance over which the shelter is effective is dependent on barrier height (h). McNaughton (1988) suggested that wind speed (u) in the lee of the windbreak, at distance x from the windbreak and height z above ground level, with an incident wind speed u_0 normal to the windbreak can be expressed as equation 4.1.

$$u/u_0 = f(x/h, z/h, h/z_0, h/L, \phi), \qquad (4.1)$$

where z_0 is the roughness length of the incident wind profile, L is the Monin-Obukhov stability length and ϕ the ratio of perforated area to total area of a windbreak (porosity).

The assumption in normalizing wind speed is that the relative effect of shelter is independent of u_0. This assumption has been supported by wind tunnel (Woodruff *et al.*, 1954) and field (Heisler and Dewalle, 1988) measurements. For artificial windbreaks the assumption that u/u_0 is constant over a range of u_0 is reasonable, but under field conditions increases in u_0 may cause a change in ϕ of a tree windbreak. Decreases in u/u_0 from 0.7 to 0.5 with increases in u_0 from 1 to 8 m s^{-1} were found by Konstantinov and Struzer (1965) and Bates (1911) behind porous windbreaks, although the degree of change of u/u_0 varied with x and z (Van Eimern *et al.*, 1964), possibly because of an increase in ϕ at high wind speeds (Konstantinov and Struzer, 1965). By contrast conifer canopies may decrease in ϕ as u_0 increases, by closing their needles like 'venetian blinds' (Van Eimern *et al.*, 1964, citing Woelfle, 1939).

The degree of turbulence behind windbreaks has been measured in both wind tunnels (Raine, 1974; Raine and Stevenson, 1977; Perera, 1981) and the field (Jacobs, 1985; Wilson, 1987). Raine and Stevenson (1977) indicated areas of high turbulence intensity (the standard deviation of the wind speed (σ_u) divided by the mean horizontal wind speed ($u_{(x,\ z)}$)) at the top of the barriers extending down to $z = 0$ at $x = 10$ to $12h$ for model fences of $\phi = 0$. Raine (1974) working with model barriers in a wind tunnel divided up the area in the lee of the windbreak into an area of low turbulence, the quiet zone dominated by bleed flow, ie. air passing through the wind break, and an area of increased turbulence, the wake zone, dominated by displacement air flow (Figure 4.1). Displacement flow is associated with vertical air movement (w), and reverse flow (air flowing in the opposite direction to the mean wind direction) (Skidmore and Hagan, 1970). This is thought to reduce the extent of effective shelter given by the windbreak, since heat and vapour transfer often increase in this zone although mean u may decrease (McNaughton, 1988). The size, position and turbulence intensity of the wake zone varies with ϕ (Raine and Stevenson, 1977; McNaughton, 1988).

4.1.2 Effect of porosity

The amount and distribution of porosity (ϕ) within a windbreak affects turbulence intensity, minimum wind speed and extent of shelter. Minimum wind speed increases as ϕ decreases, but the size of the decrease varies with both x and z.

Behind very dense windbreaks u_0 is reached at a shorter distance than behind medium dense windbreaks of higher ϕ (Nageli, 1946; cited by Van Eimern *et al.*, 1964). This effect may be caused by the development of a pressure difference behind a dense windbreak forcing downward air movement, increasing turbulence (ie. the w component of wind), and thus reducing the extent of the shelter (McNaughton, 1988; see Figure 4.1).

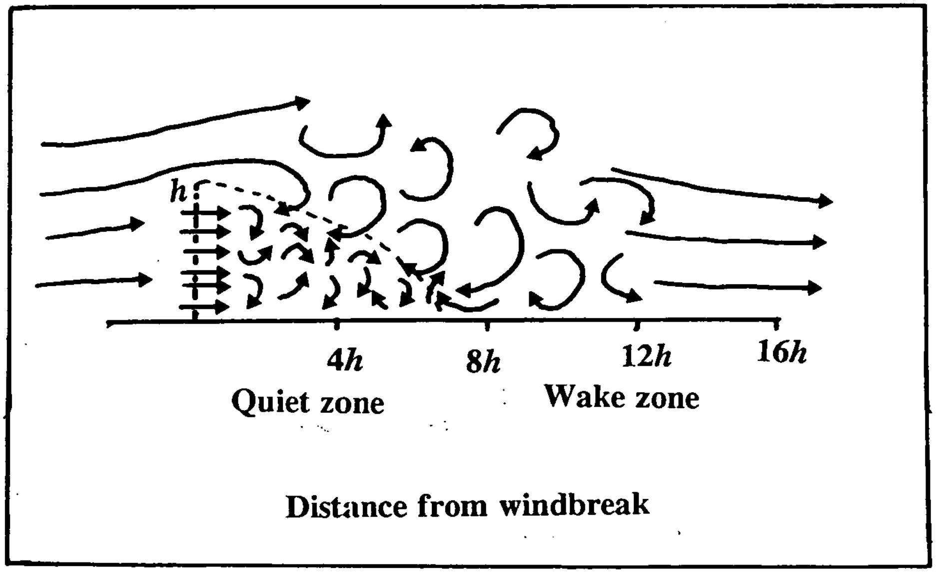


Figure 4.1 A simplified view of the air flow round a porous barrier, with the formation of a quiet zone in the immediate lee of the windbreak, and a more turbulent wake zone at a distance of 6 to 10h (from Raine, 1974).

Data from Woodruff *et al.* (1954), and Caborn (1957) suggested that this effect was overestimated by Nageli (1946), whose results can in part be attributed to higher turbulence in the incident wind profile for his very dense windbreak (Heisler and Dewalle, 1988). Work in a wind tunnel (Raine and Stevenson, 1977; Perera, 1981) and field studies (Skidmore and Hagen, 1970) support the idea that windbreaks with low ϕ reduce u at a larger distance behind the windbreak than was suggested by Nageli (1946), however low ϕ windbreaks will generate larger turbulent intensities than those with higher ϕ (Raine, 1974; Perara, 1981).

Larger porosity of windbreaks near the ground may be an advantage, allowing air flow and preventing the build up of pressure differences (Onyewotu, 1983; Rosenberg *et al.*, 1983), or a disadvantage, increasing u close to the ground in the immediate lee of the windbreak (Jensen, 1954). For example Kuhlewind *et al.* (1955) (cited by Van Eimern *et al.*, 1964) found u/u_0 increased to 1.2 in the immediate lee ($1h$) of a two-row-windbreak with a gap below the canopy and decreased to 1.0 at around $x = 3.5h$. Inclusion of ϕ of the lower half of the windbreak in a model to predict minimum wind speeds agreed well with measured values, however inclusion in the model of ϕ of the upper part of the windbreak did not increase the accuracy of the model (Heisler and Dewalle, 1988). The importance of the ϕ of the lower half of the windbreak is supported by Miller *et al.* (1975) who showed that a young high ϕ windbreak with lower ϕ in its lower half of the windbreak gave effective shelter ($u/u_0 = 0.6$ at $x = 2h$).

Moysey and McPherson (1966) used a wind tunnel to show average reductions of u/u_0 over a distance of $6h$ were largest for $\phi = 0.32$ when measured at $z = h/4$, whereas $\phi = 0.16$ was more effective when measured at $z = h/2$. Konstantinov and Struzer (1965) recommended ϕ between 0.2 to 0.4 for most field windbreaks.

4.1.3 Effect of surface roughness

The turbulence of the incident flow influences the effectiveness of a windbreak and can be characterised by the surface roughness z_0, (Bates, 1911; Jensen, 1954; Heisler and Dewalle, 1988). Values of z_0 calculated from undisturbed wind profiles vary with the type and height of the underlying vegetation (Monteith and Unsworth, 1990) and u_0 (Miller *et al.*, 1975). z_0 is also affected by atmospheric stability (Section 4.1.4). Reducing h/z_0 will generally reduce shelter behind a windbreak: Seginer (1975a) showed using a barrier $\phi = 0.5$ that the effect on u/u_0 of a change in z_0 was larger in the wake zone than the quiet zone (Figure 4.1).

4.1.4 Influence of stability

Atmospheric stability is usually expressed either as the Richardson number (Ri) at $z = h$ or as the Monin-Obukov length (L) (definitions of these terms and the relationship between them are given in Monteith and Unsworth, 1990). Seginer

(1975a), using Ri, fitted an empirical function of the form:

$$u/u_o = 1 - be^{-a\mathrm{Ri}} \qquad (4.2)$$

where a and b are empirical constants. As Ri becomes negative (ie. more unstable conditions) the effectiveness of a windbreak decreases (Miller *et al.*, 1975). Jacobs (1984) working with a solid fence, found that the slowest recovery of wind speed near the surface occurred in near-neutral conditions (h/L = -0.002), with recovery being faster in unstable conditions (h/L = -0.07). Jacobs (1985) reported that turbulence at $z = h/3$ behind a solid fence exceeded that in the open under unstable conditions, but was substantially reduced under stable conditions, remaining below that experienced in the undisturbed flow.

4.1.5 Effect of incident wind angle

The angle of incidence of the wind (Θ) changes the area protected, maximum protection is often expected for winds perpendicular to the windbreak ($\Theta = 90^o$), and minimum shelter for parallel winds ($\Theta = 0^o$). Reduction in wind speed of the order of 10 to 25 % have been recorded close to the windbreak for $\Theta = 0^o$ (Van Eimern *et al.*, 1964; Konstantinov and Struzer, 1965; Rollin, 1983), probably as a result of absorption of momentum by nearby tree crowns creating horizontal shear. Horizontal logarithmic wind profiles can be calculated and a horizontal z_o derived (Konstantinov and Struzer, 1965) demonstrating that rough edged windbreaks are more effective in parallel winds than smooth fences.

Rollin (1983) found that u/u_o at $x = 4h$ decreased as Θ increased towards 90^o for a medium porous barrier (ϕ = 0.3 to 0.4). Seginer (1975b) expressed the effect of Θ on u/u_o as:

$$u/u_o = a + b(1 - \sin\Theta) \qquad (4.3)$$

where a and b are empirical constants that depend on both x and h/z_o. Using this formulation he found that the largest effect of Θ was at $x = 8h$, decreasing towards $x = 50h$. Jacobs (1984), using a solid fence found no reduction of shelter until $\Theta < 45^o$. The reduction of shelter of vertical slat fences for oblique winds may result from a change in ϕ with Θ, changes with horizontal slat fences are likely to be less. Konstantinov and Struzer (1965) showed that the change in efficiency of a windbreak with Θ depended on ϕ, with windbreaks of $\phi = 0.8$ having maximum effectiveness at $\Theta = 30^{\circ}$, possibly resulting from increased path length through the windbreak.

4.1.6 Effect of multiple windbreaks and choice of valid control

There are two possible approaches to defining a control for investigations with established windbreaks: 1) comparing the effect of a windbreak in terms of the microclimate incident on the windbreak, ie. treating the windbreak in isolation, or 2) comparing the effect of a series of parallel windbreaks with the microclimate in the absence of windbreaks. The second approach requires measurements from outside the influence of the windbreak system, which may need to be a substantial distance away and consequently may be in an area with a different wind regime.

Second and third windbreaks planted at distances greater than 10*h* apart (no data for networks of windbreaks planted at smaller distances) do not show a cumulative effect, but have a reduced efficiency resulting from the increased turbulence of the incident flow (Van Eimern *et al.*, 1964; Heisler and Dewalle, 1988). Large networks of windbreaks will develop their own characteristic boundary layer that might take several kilometres to develop (Plate, 1971). The optimum spacing of windbreaks depends on the purpose for which the windbreak is required as well as environmental conditions such as u_0 and z_0.

Two different wind profiles may be taken as a reference i) that within the windbreak system on the windward side of the windbreak 'windward' and, ii) that of an unsheltered field outside the influence of the windbreak 'unsheltered'.

The work reported in this chapter aims to characterize the wind pattern behind the windbreak, and how it changed under different incident wind conditions over the season. The measurements focussed upon the effect of shelter on the crop and so measurements were made just above crop height (Sections 3.2.5 and 3.3.1.2).

4.2 RESULTS

The results presented in the following section were collected using the configurations described in Sections 3.3.1 and 3.3.3. For clarification Figure 4.2 shows the orientation of the windbreak and direction of prevailing and storm winds, wind directions are given as values of Θ, where 0^{o} is south and 90^{o} is west.

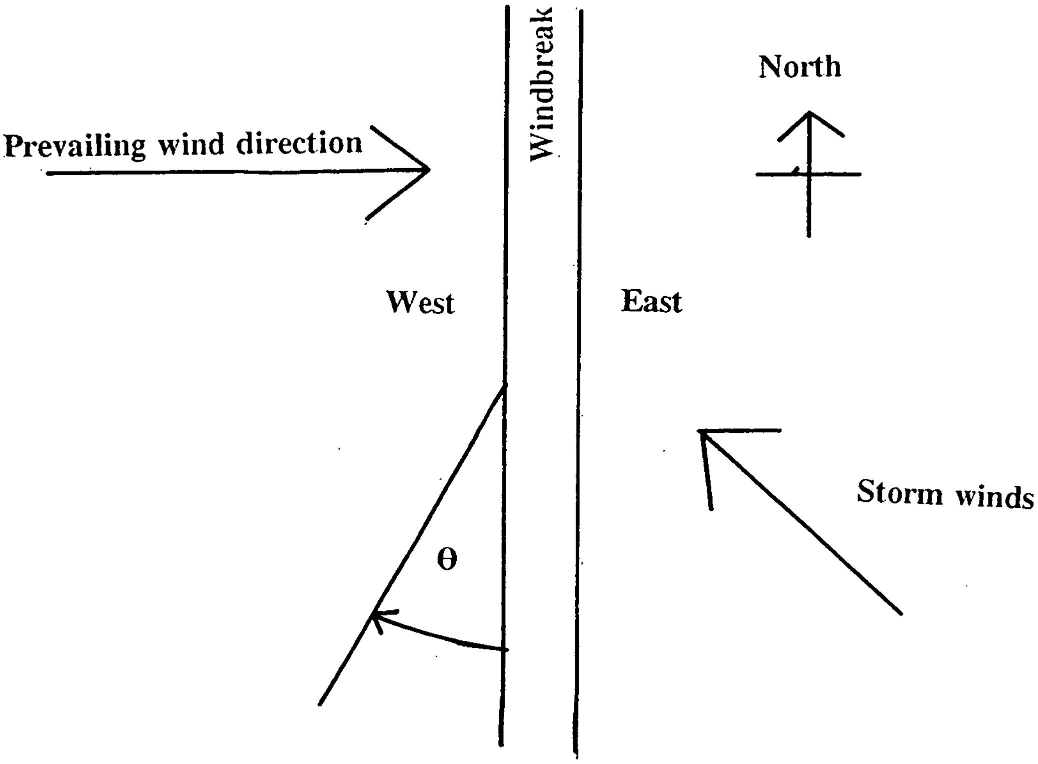


Figure 4.2 Orientation of windbreak with respect to prevailing wind direction. Θ is the angle of incidence of the wind.

4.2.1 Horizontal wind speed and wind variability

In Configuration A wind speeds (u) and wind variabilities (σ_u/u) were measured at (h_c + 20 cm), where h_c is crop height which varied from $0.07h$ at the beginning of the season to $z = 0.33h$ by the end of the season. The eddy size 20 cm above the crop may be in the order of 20 to 30 cm. Since wind speed measurements were taken every 20 seconds with cup anemometers σ_u/u may not give an accurate characterization of the turbulence regime above the crop. So the term wind variability (WV) has been used for σ_u/u. When the wind variability has been normalized to incident wind conditions the term normalized wind variability has been used (NWV). Wind speeds and wind variabilities were normalized with respect to the incident conditions at (h_c + 20 cm), 6*h* in front of the windbreak.

An example of a typical wind regime (Julian day 249) consisting of the diurnal wind pattern (Figure 4.3a), wind direction (Figure 4.3b) and wind variability (Figure 4.3c). While Θ was approximately 80°, u/u_0 at 3*h*, 6*h*, 10*h* and 1*h* were around 0.45, 0.60, 0.90 and 1.10, respectively. At 18.00 h Θ decreased below zero (south-east) indicating storm winds and u/u_0 exceeded 1.0, since the winds were incident on the previously leeward side of the windbreak. Windward wind variability (WV) remained ca. 0.3 to 0.4 for most of the day, increasing to 0.8 at 18.00 h. Normalized wind variabilities (NWV) $(\sigma_u/u)/(\sigma_{uo}/u_0)$ measured at 1*h* and 3*h* were 1.0 or less and, at 6*h* and 10*h* were 1.5 to 2.0.

4.2.1.1 Group Divisions

Data were separated into seventeen groups for wind direction to give maximum detail of change of shelter with wind direction and sufficient observations within each group to enable viable statistical analysis. Six time intervals were selected after analysing the data in weekly units and grouping similar periods together, summarized in Table 4.1.

The mean normalized wind speed (mean *u*/mean u_0), normalized wind variabilities (mean WV/ mean WV_0) and standard errors of each group were calculated for each time interval, excluding values when wind speeds were less than the starting velocity of the anemometer.

Tables of the change in normalized wind speed and normalized wind variability with wind direction for each time interval are presented in Appendix V. Standard errors shown in the tables are pooled for all four distances from the windbreak.

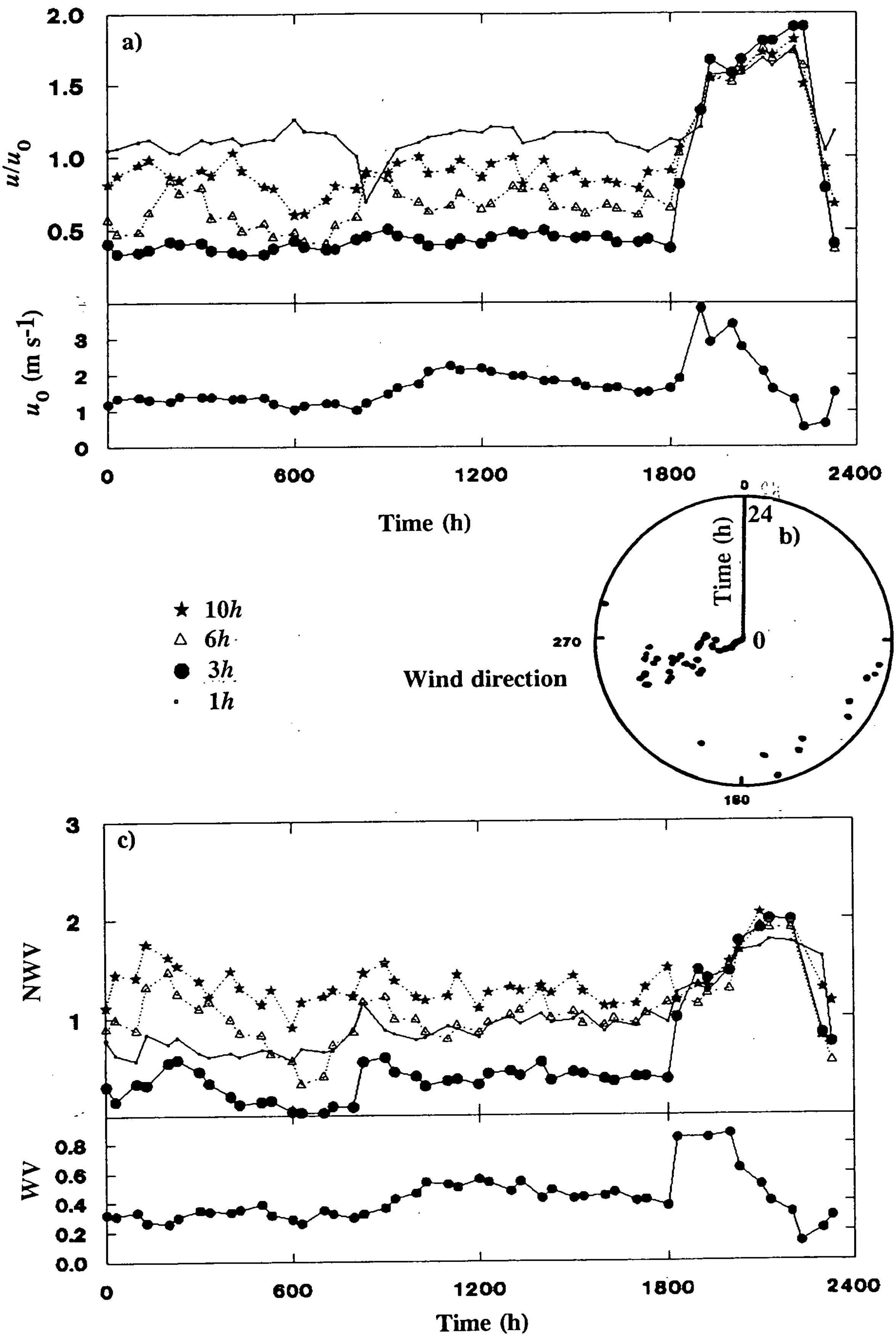


Figure 4.3 Diurnal wind patterns for julian day 249, a) normalized wind speed (u/u_0) at 1*h*, 3*h*, 6*h*, and 10*h* and incident wind speed (u_0), b) wind direction (bearing) and c) normalized wind variability (NWV) at 1*h*, 3*h*, 6*h*, and 10*h* and incident wind variability (WV)

T - test comparisons were made between individual groups using the pooled standard error of the two groups compared. Groups containing less than two observations were not included in the analysis.

Table 4.1 Divisions of wind data into wind directions for analysis over time intervals over the season for configuration A.

Group	Wind direction (degrees)	Θ (degrees)	Interval	Julian Day
1	1 - 60	-180 - -120	A	201 - 221
2	61 - 120	-119 - -60	B	222 - 235
3	121 - 180	-59 - 0	C	236 - 250
4	181 - 200	1 - 20	D	251 - 264
5	201 - 220	21 - 40	E	265 - 279
6	221 - 230	41 - 50	F	280 - 294
7	231 - 240	51 - 60		
8	241 - 250	61 - 70		
9	251 - 260	71 - 80		
10	261 - 270	81 - 90		
11	271 - 280	91 - 100		
12	281 - 290	101 - 110		
13	291 - 300	111 - 120		
14	301 - 310	121 - 130		
15	311 - 320	131 - 140		
16	321 - 340	141 - 160		
17	341 - 360	161 - 180		

4.2.1.2 Change of normalized wind speed and wind variability over the season

Interval A : days 200-221 : As Θ approached 0° (south) u/u_0 was significantly lower near the windbreak than at $6h$ or $10h$. However by 30° positions were reversed with u/u_0 lowest at $6h$, and highest at $1h$ (Figure 4.4a). u/u_0 at $1h$

exceeded the incident wind speed from $70^o < \Theta < 110^o$ peaking at 90^o, ie. perpendicular to the windbreak. NWVs were significantly lower at $1h$ and $3h$ than at $6h$ and $10h$ (Figure 4.5a), decreasing with increasing Θ towards a minimum at 90^o of 0.78 and then increased towards 180^o.

Interval B : days 224-235 : Interval B had a similar pattern to A, westerly winds giving minimum u/u_0 at 30^o. No significant difference of u/u_0 with wind direction was found between $3h$ and $6h$ until 75^o, when u/u_0 at $6h$ was lowest. The differences between $3h$, $6h$ and $10h$ decreased above 105^o. NWVs did not differ greatly from 1.0, with lowest values at 90^o. Significantly higher NWVs were measured at $6h$ and $10h$ than $1h$ and $3h$ for $45^o < \Theta < 105^o$.

Interval C : days 236 - 250 : Figure 4.4b shows that the wind speed at $3h$ was significantly lower than at all the other positions for $30^o < \Theta < 135^o$ and $6h$ was significantly lower than $10h$ for $45^o < \Theta < 95^o$. Minimum wind speeds occurred for $75^o < \Theta < 95^o$. For $\Theta > 0$ NWVs at $6h$ and $10h$ were significantly higher than the NWVs at $1h$ and $3h$ which remained around or just under 1.0 (Figure 4.5b).

Interval D : Days 251 - 264 : The pattern of interval C continued over interval D, with u/u_0 at $3h$ being significantly lower than at all other positions. u/u_0 at $6h$ was less than at $10h$ for $45^o < \Theta < 115^o$ which had a lower u/u_0 than $1h$ which peaked at 90^o. NWVs were significantly higher at $6h$ and $10h$ than $1h$ and $3h$, for $55^o < \Theta < 115^o$.

Interval E : Days 265-279 : u/u_0 at $3h$ remained significantly lower than at all the other positions, although the differences in u/u_0 between the other positions were smaller (Figure 4.4c). u/u_0 at $1h$ was lower than in the previous intervals. NWVs were around 1.0, with significantly lower values at $3h$ than at the other positions; on average the highest NWV was at $10h$ (Figure 4.5c).

Interval F : Days 280 - 294 : Low wind speeds were found at $3h$ and $1h$, with higher u/u_0 at $6h$ and $10h$. Fewer observations were collected resulting from lower wind speeds and a change in wind direction towards the south - east.

4.2.1.3 Summary

A summary of mean u/u_0 over $10^o < \Theta < 125^o$ is presented in Table 4.2, and mean NWV in Table 4.3.

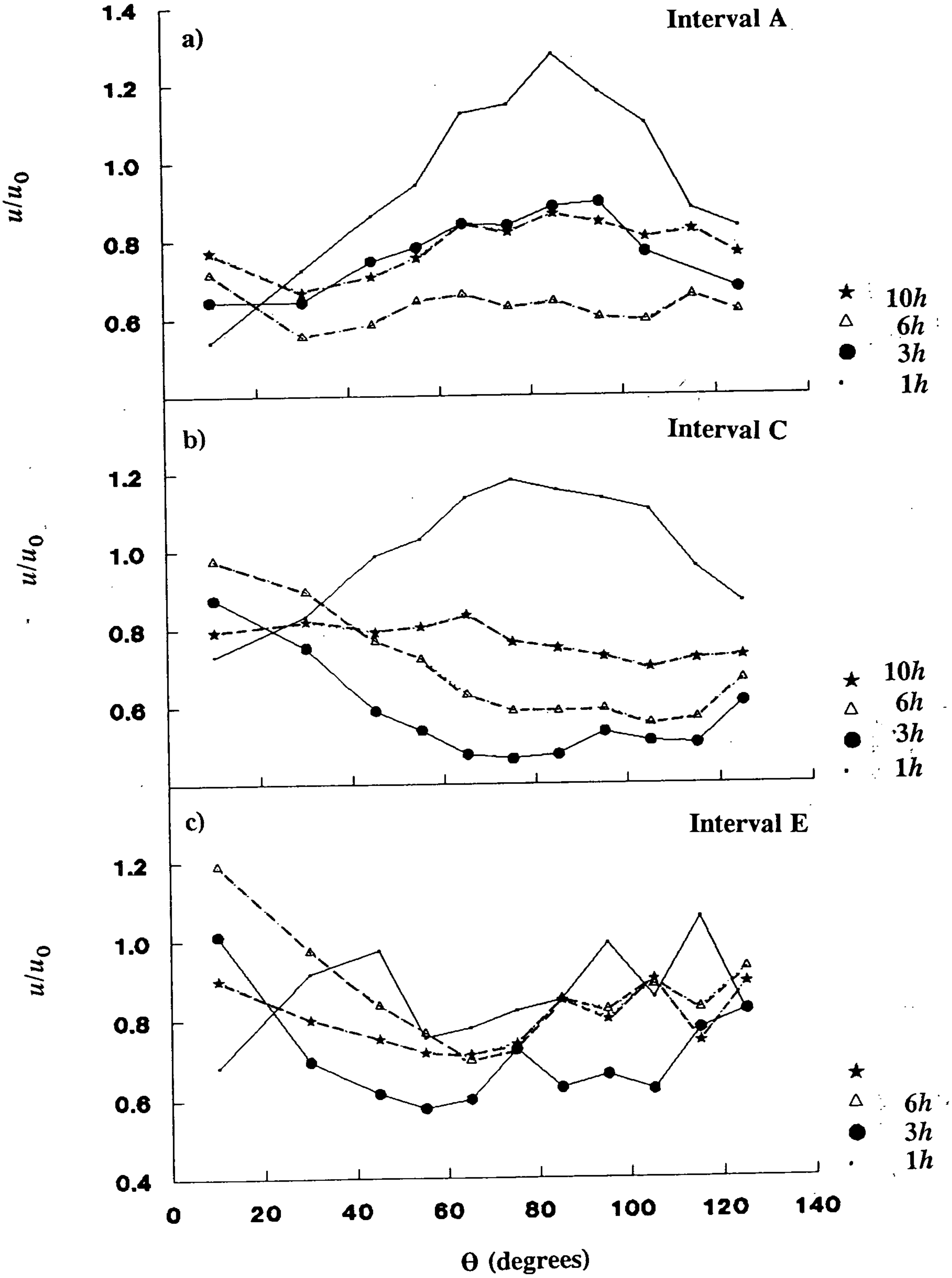


Figure 4.4 Change of normalized wind speed (u/u_0) with angle of incidence of the wind (Θ) for four distances behind a windbreak over the season. a) interval A, b) interval C and c) interval E.

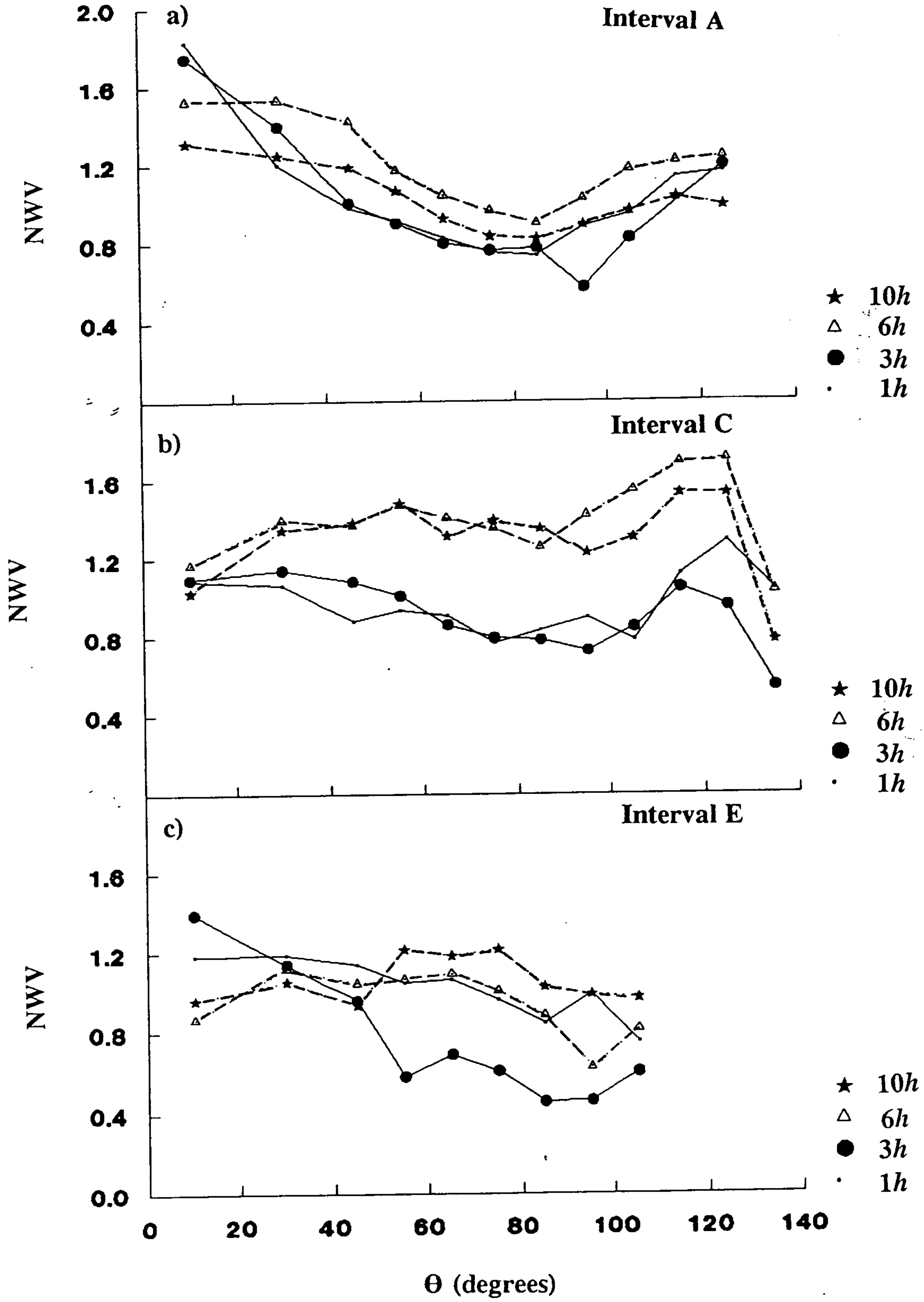


Figure 4.5 Change of normalized wind variability (NWV) with angle of incidence of the wind (Θ) for four distances behind a windbreak over the season. a) interval A, b) interval C and c) interval E.

Table 4.2 Mean normalized wind speed for four distances from the windbreak for different times over the season, for $10^{o} < \Theta < 125^{o}$. The weighted mean was calculated by weighting the mean u/u_0 by the proportion of time the wind was coming from the particular direction.

Interval	mean				weighted mean			
	1*h*	3*h*	6*h*	10*h*	1*h*	3*h*	6*h*	10*h*
A	0.96	0.77	0.63	0.79	0.87	0.74	0.62	0.75
B	1.02	0.71	0.71	0.82	1.10	0.70	0.69	0.79
C	1.01	0.58	0.69	0.77	1.05	0.56	0.70	0.79
D	0.87	0.51	0.73	0.78	0.85	0.55	0.75	0.79
E	0.86	0.70	0.87	0.80	0.82	0.72	0.88	0.79
F	0.75	0.42	1.16	1.02	0.82	0.56	1.13	1.01
Mean	0.94	0.65	0.73	0.79	0.94	0.65	0.73	0.78

Table 4.3 Mean normalized wind variabilities for four distances from the windbreak for different times over the season, for $10^{o} < \Theta < 125^{o}$.

Interval	mean				weighted mean			
	1*h*	3*h*	6*h*	10*h*	1*h*	3*h*	6*h*	10*h*
A	1.03	1.06	1.20	1.03	1.12	1.16	1.32	1.13
B	1.02	1.00	1.16	1.11	0.95	0.97	1.16	1.15
C	0.96	0.94	1.44	1.36	0.92	0.94	1.39	1.35
D	0.98	0.83	1.20	1.17	1.00	0.91	1.17	1.17
E	1.02	0.75	0.95	1.06	1.08	0.92	0.99	1.07
F	0.78	0.66	0.77	1.03	0.74	0.72	0.79	1.05
mean	0.97	0.87	1.12	1.13	1.01	0.94	1.14	1.15

Changes of u/u_0 and NWV over the season are shown in Figures 4.6a and b, (data from Tables 4.2 and 4.3). These changes result from a combination of the change in measurement height with millet growth over the cropping season and a decrease in porosity of the lower half of the windbreak by the growth of millet windward of the windbreak.

4.2.2 Response of normalized wind speed to wind angle

The data for intervals A to D were analysed with eq 4.3, regressions for intervals A and B were poor, but intervals C and D gave good correlations for most distances from the windbreak. An example from interval C is shown in Figure 4.7., each data point represents the average of two weeks data. Good regressions ($r^2 > 0.9$, $n = 7$) were also found for $3h$ and $6h$ for interval D, with coefficients similar to those in Figure 4.7. Generally the equation gave good predictions for quiet zone response to Θ, when porosity of the windbreak was low.

4.2.3 Influence of incident wind speed and porosity

Configuration D (Section 3.3.4) was set up on a similar 2 row neem windbreak to configuration A, in the dry season after the crop had been harvested and the straw ploughed into the field. Measurements of wind speed were made at $-6h$, $1h$, $3h$, $6h$ and $10h$ at two different heights (1 m, 3 m) simultaneously, to give the air flow behind a windbreak with and without the gap at the bottom of the canopy blocked off (for details of treatment see Section 2.2.3). The treatment changed the ϕ of the lower part of the canopy from $\phi = 0.63$ to $\phi = 0.0$, and the average ϕ of the canopy from 0.27 to 0.09.

Data over a 2-week-period were selected for $80^\circ < \Theta < 100^\circ$. At $z = 1$ m u/u_0 did not change with u_0, however at $z = 3$ m u/u_0 decreased sharply on both windbreak porosities (Figure 4.8a - d). The transition occurred at $u_0 = 2.8$ m s^{-1} behind the open and $u_0 = 4$ m s^{-1} behind the dense windbreak.

Figures 4.9a - b shows that although there was no change in u/u_0 at $z = 1$ m, at 3 m u/u_0 was around 0.25 lower above the transition point , the reduction being larger behind the open than the dense windbreak and with increasing distance from the windbreak. At $z = 1$ m, $u/u_0(6h) < u/u_0(3h)$, whereas at 3 m $u/u_0(3h) <$

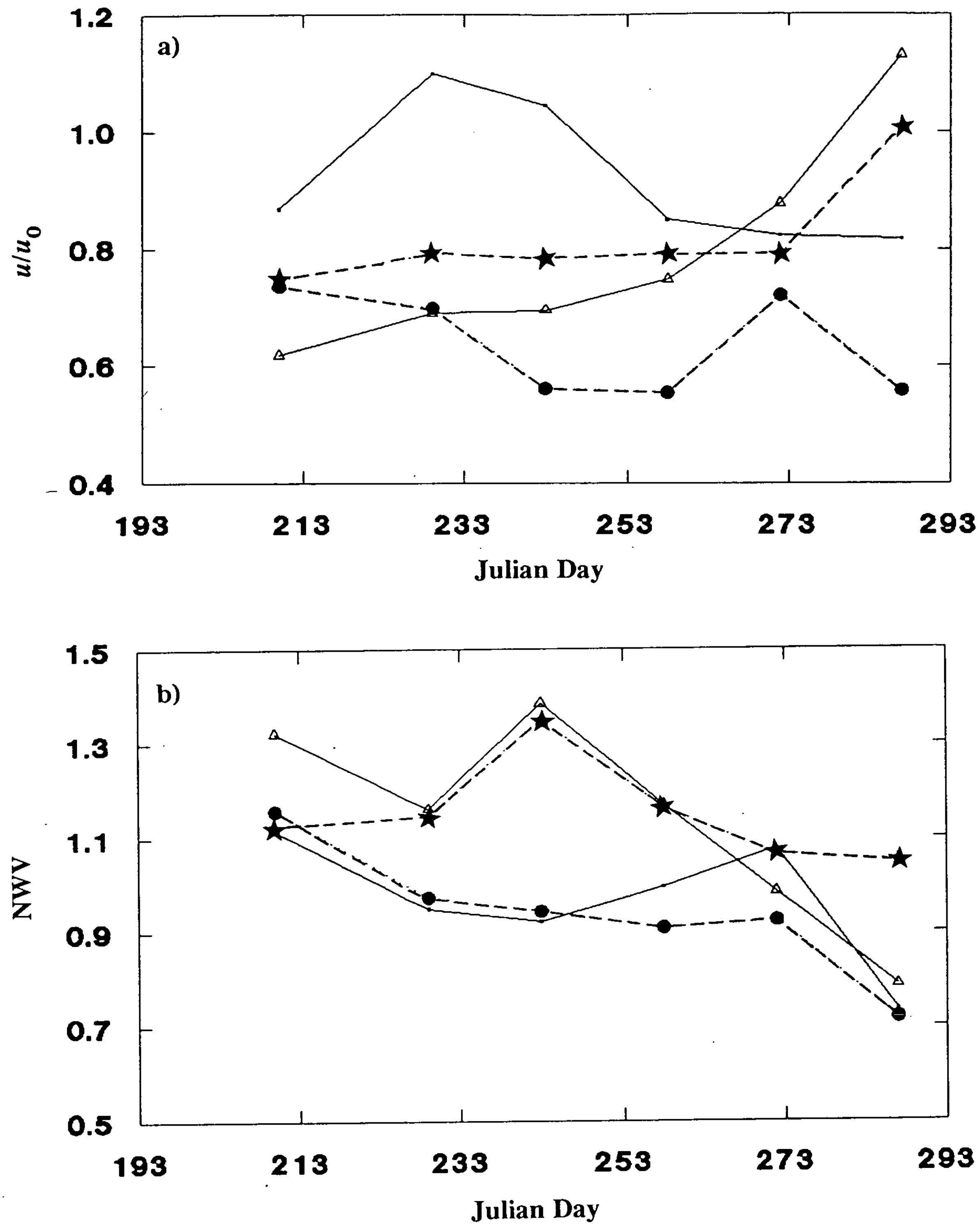


Figure 4.6 Change of a) normalized wind speed (u/u_0) averaged for 10° > Θ > 125° for four distances behind a windbreak over the season. b) normalized wind variability (NWV) averaged for 10° > Θ > 125° for four distances behind a windbreak over the season. 1*h* (•), 3*h* (●), 6*h* (△), and 10*h* (★).

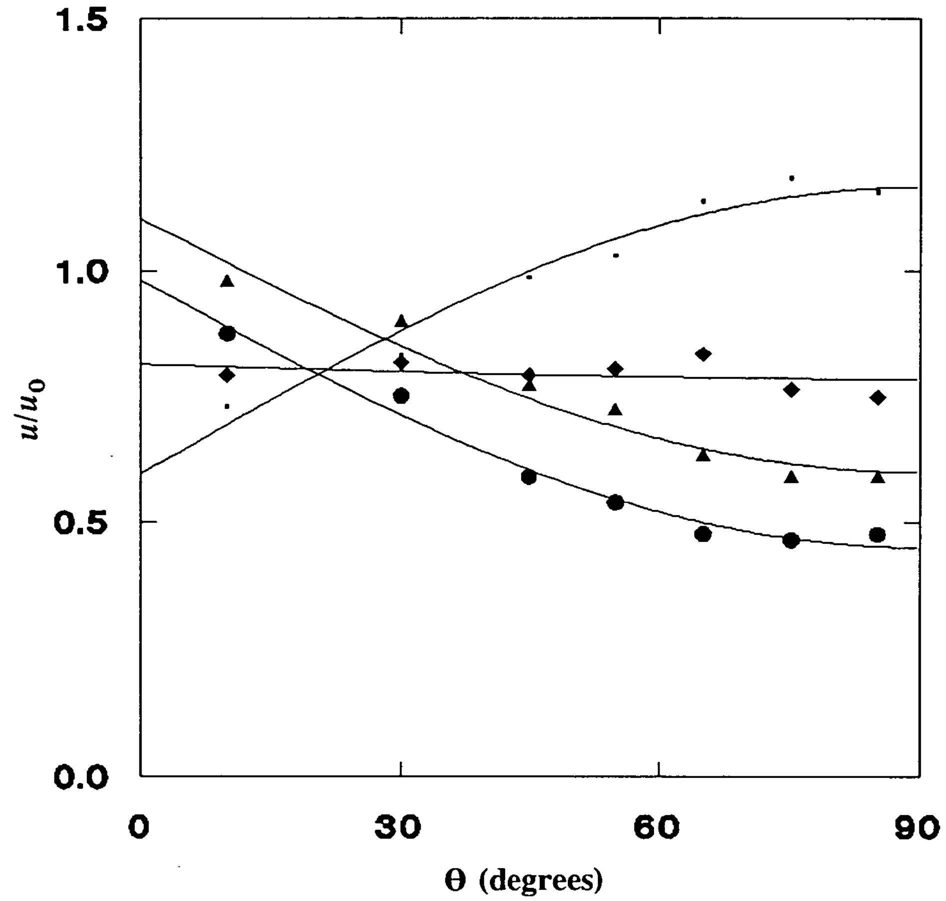


Figure 4.7 Change of u/u_0 with Θ for interval C compared with eq. 4.3, for four distances behind the windbreak, 1*h* (•), ($u/u_0 = 1.17 - 0.57(1 - \sin\Theta)$, $r^2 = 0.96$), 3*h* (●), ($u/u_0 = 0.45 + 0.53(1 - \sin\Theta)$, $r^2 = 0.98$), 6*h* (▲), ($u/u_0 = 0.60 + 0.50(1 - \sin\Theta)$, $r^2 = 0.96$), 10*h* (◆) $u/u_0 = 0.79 - 0.03(1 - \sin\Theta)$, $r^2 = 0.09$.

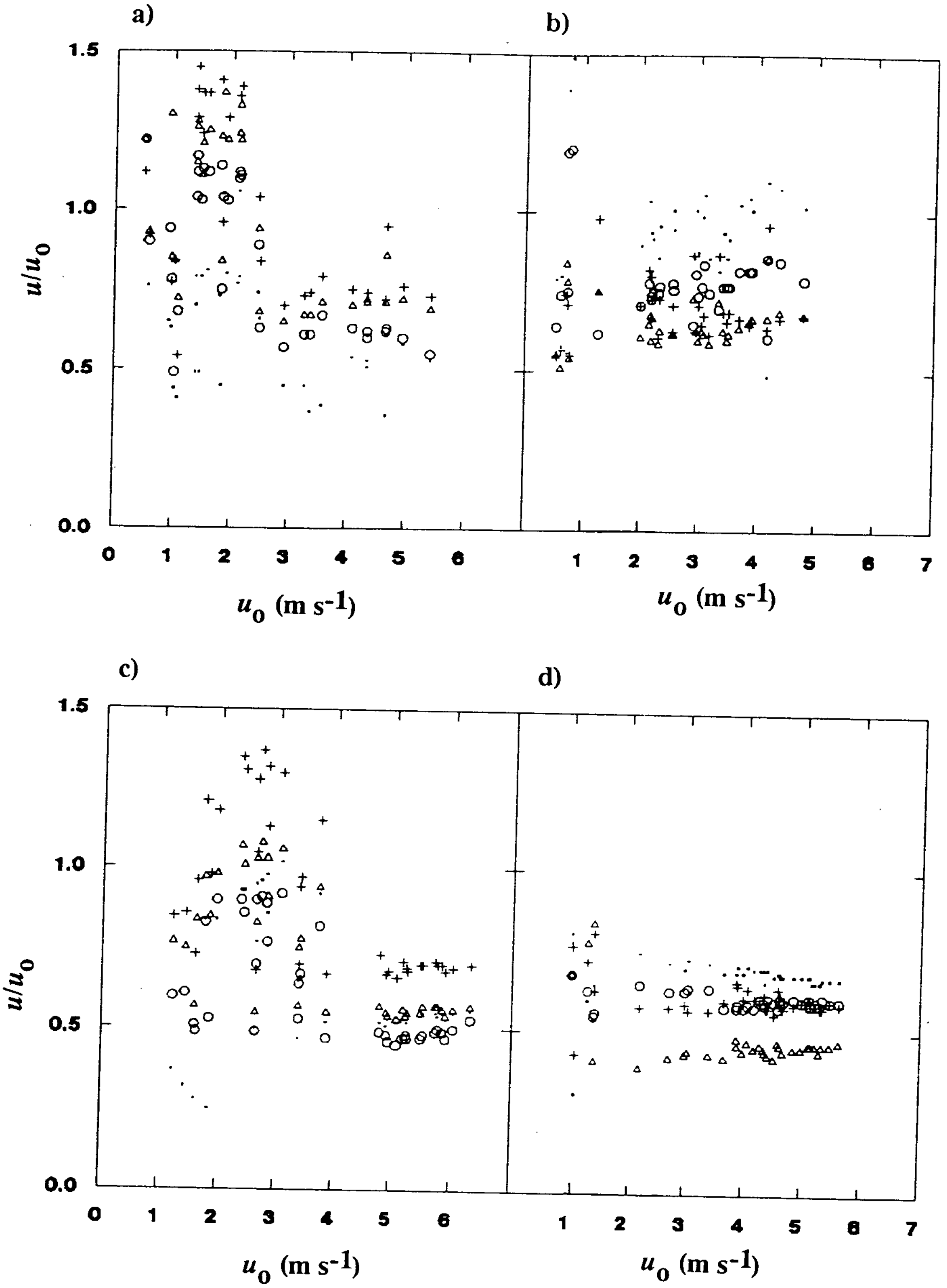


Figure 4.8 The influence of incident wind speed (u_0) on normalized wind speed (u/u_0) at 1*h* (•), 3*h* (○), 6*h* (△) and 10h (+), behind an open windbreak measured at a) z = 3 m, and b) z = 1 m, and behind a dense windbreak measured at c) z = 3 m, and d) z = 1 m.

$u/u_o(6h)$. There were substantial reductions in u/u_o from the reduction of porosity under all conditions, except at $1h$ and $z = 3$ m, which was just behind the tree canopy, the reductions in u/u_o were smallest at $10h$.

4.2.4 Changes in normalized wind speed and wind variabilities with height and distance

Wind profiles and wind variabilities were measured up to a $z = 5$ m, at $1h$, $3h$, $6h$, $10h$, $16.7h$ and $20h$, configuration C. All measurements were made in the same field as configuration A, except for those made at $20h$. Day-time measurements were selected for $60^o < \Theta < 120^o$ and normalized against the wind speed and wind variability at $z = 5$ m and $x = -6h$ (ie on the windward side of the windbreak).

Wind speed reductions occurred over $3h$ to $6h$ with higher wind speeds occurring at $15h$ (Figure 4.10a), contours were smoothed using a least squares regression procedure. High NWVs occurred at the top of the windbreak and at about $10h$, near the ground (Figure 4.10b). NWV decreased towards $15h$, but wind speed increased, so actual turbulence may have remained high up to $15h$, suggesting a quiet zone extending to about $8h$, and a wake zone to $20h$. h_c varied with the time of measurement and was 2.00 m, 2.14 m, 1.78 m, 1.38 m, 1.00 m and 1.20 m for $1h$, $3h$, $6h$, $10h$, $16.7h$, and $20h$, respectively. The pattern of wind speeds were very similar to those measured by Woodruff (1956) for a three row model windbreak spaced $24h$ apart in a wind tunnel.

4.2.5 Boundary layer conductance

Heated leaf replicas were used to measure the boundary layer conductance at four positions behind the windbreak. As with the horizontal wind speed these data were grouped with respect to Θ. Five groups were used for Θ, $-180^o < \Theta < 0^o$, $1^o < \Theta < 30^o$, $31^o < \Theta < 90^o$, $91^o < \Theta < 140^o$ and $141^o < \Theta < 180^o$. Data were also divided into time intervals, see Table 4.1. Data were excluded from the analysis if there was water on the plates from dew or rain, or the power running through the circuit was too low to give measurable temperature differences.

Since upwind boundary layer conductances were not measured, boundary layer

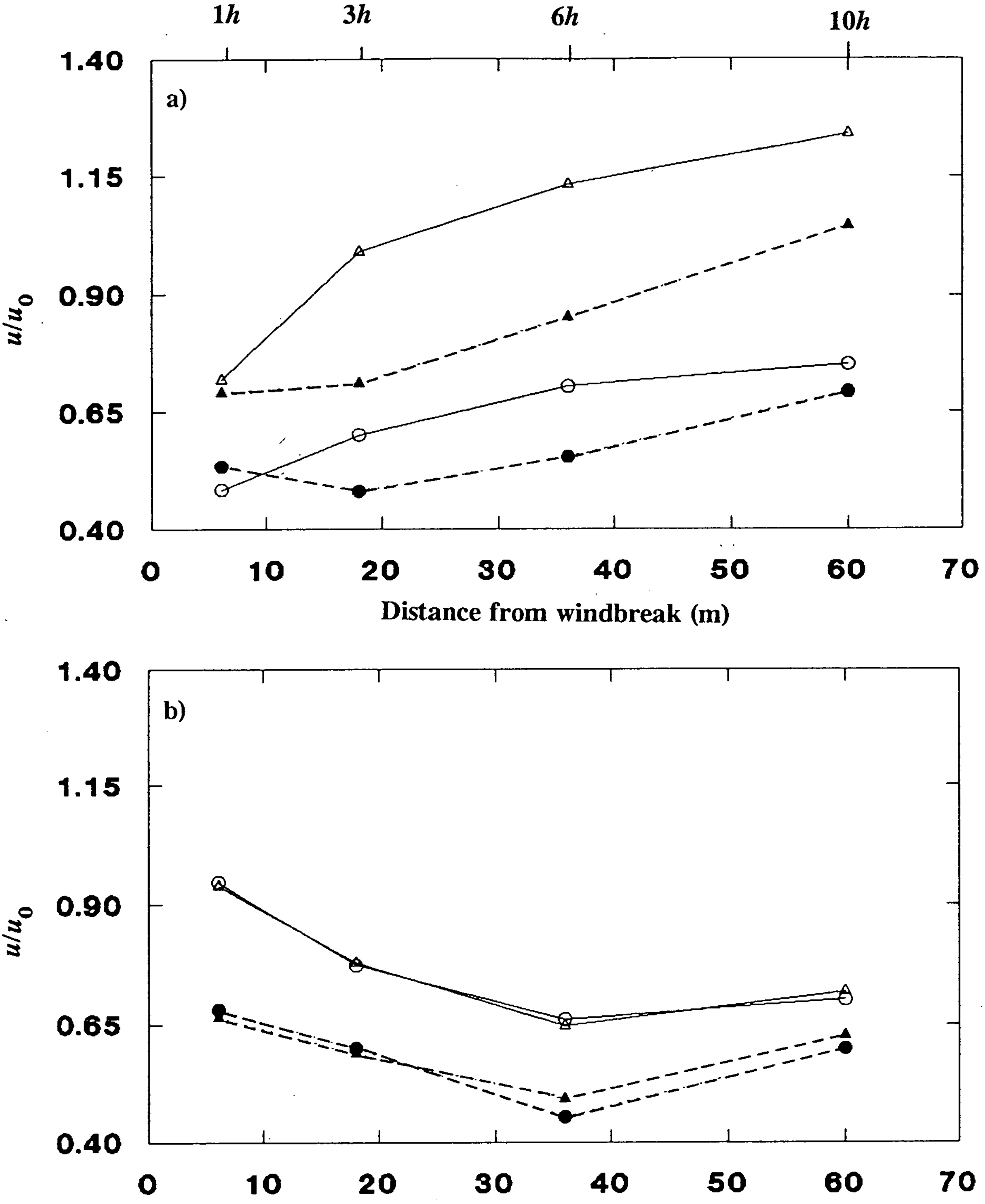


Figure 4.9 The influence of incident wind speed, height of measurement and porosity of windbreak on the change of u/u_0 with distance behind a windbreak with no crop. a) Measurements taken at z = 3 m, and b) measurements taken at z = 1 m. Low wind speed and open windbreak (△), low wind speed and dense windbreak (▲), high wind speed and open windbreak (○), high wind speed and dense windbreak (●). Data points are averages over two weeks for Θ = 90° ± 10°.

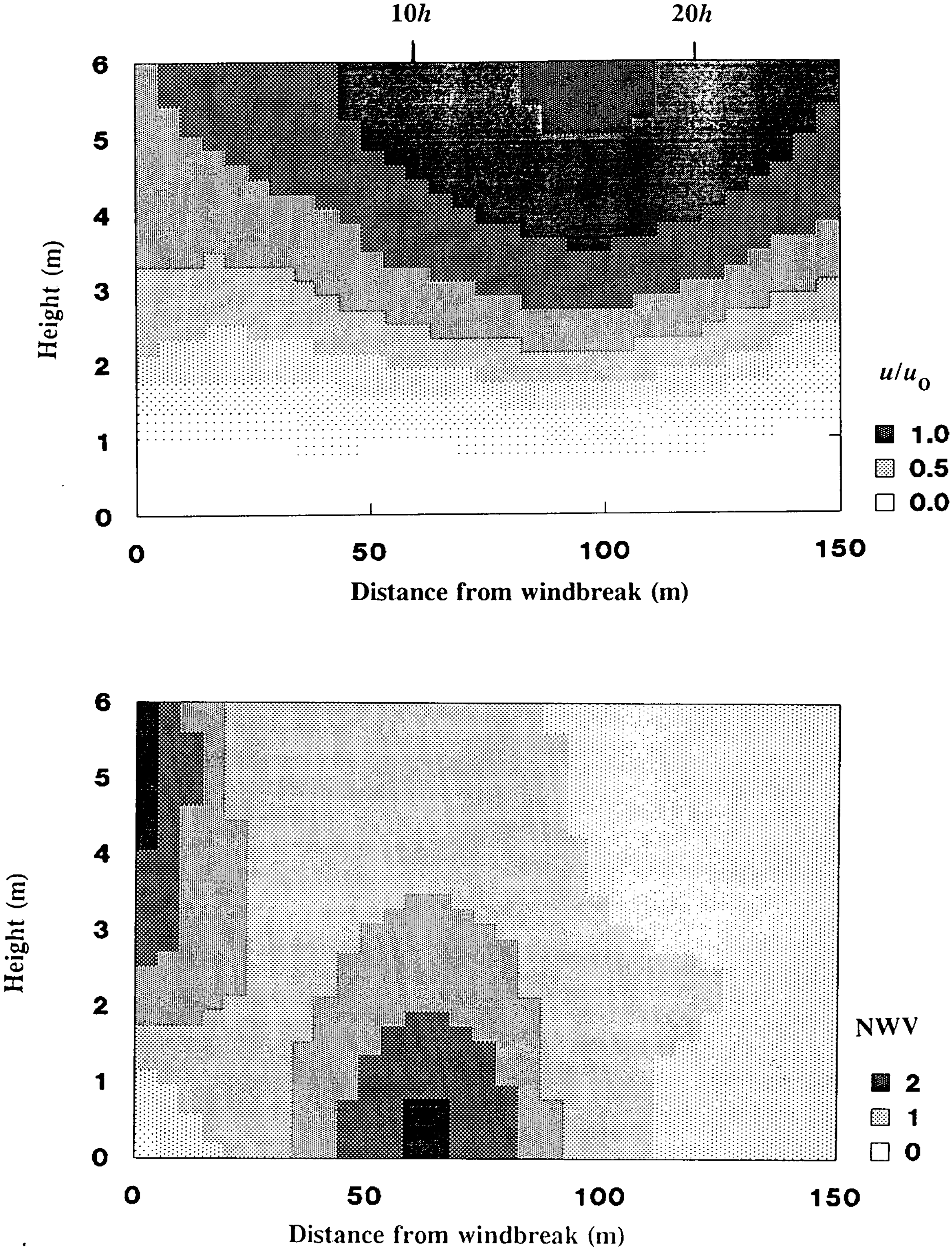


Figure 4.10 Pattern of a) u/u_0 and b) NWV at the end of the cropping season behind a windbreak. Values are normalized to wind speeds and turbulence intensities at $z = 5$ m, and $x = -6h$. Smoothing is carried out using a least squares method.

conductances were normalized against conductance at 10*h*, to allow statistical analysis of the differences between distances from the windbreak. Figures 4.11a - c show the normalized boundary layer conductance for the three time intervals A, C and F.

4.2.5.1 Change of boundary layer conductance with wind direction and time

Boundary layer conductance at 1*h* remained the highest over the season increasing towards $\Theta = 90^o$. At the start of the season (interval A) smallest conductances occurred at 6*h* but by interval B conductances at 3*h*, become significantly smaller than 6*h* for $0^o < \Theta < 30^o$. The pattern established in interval C (Figure 4.11b) of $g_a/g_{a(10h)}$ at 1*h* > at 10*h* > at 6*h* > at 3*h* continued to the end of the season (Figure 4.11c).

4.2.5.2 Relationship between normalized wind speed and normalized boundary layer conductance

The comparison of $u/u_{(10h)}$ and $g_a/g_{a(10h)}$, where $u_{(10h)}$ and $g_{a(10h)}$ were measured at 10*h* is presented in Table 4.4.

Table 4.4 Wind speed ($u/u_{(10h)}$) and boundary layer conductance ($g_a/g_{a(10h)}$) normalized to 10*h* averaged for $30^o < \Theta < 110^o$.

Interval	1*h*		3*h*		6*h*	
	($u/u_{(10h)}$)	($g_a/g_{a(10h)}$)	($u/u_{(10h)}$)	($g_a/g_{a(10h)}$)	($u/u_{(10h)}$)	($g_a/g_{a(10h)}$)
A	1.25	1.44	0.97	1.09	0.77	0.96
B	1.30	1.34	0.83	0.91	0.86	0.88
C	1.36	1.30	0.71	0.74	0.85	0.88

The data indicate that shelter was similar both in terms of $u/u_{(10h)}$ as $g_a/g_{a(10h)}$ found using the heated leaf replicas, but $g_a/g_{a(10h)}$ was usually higher than the

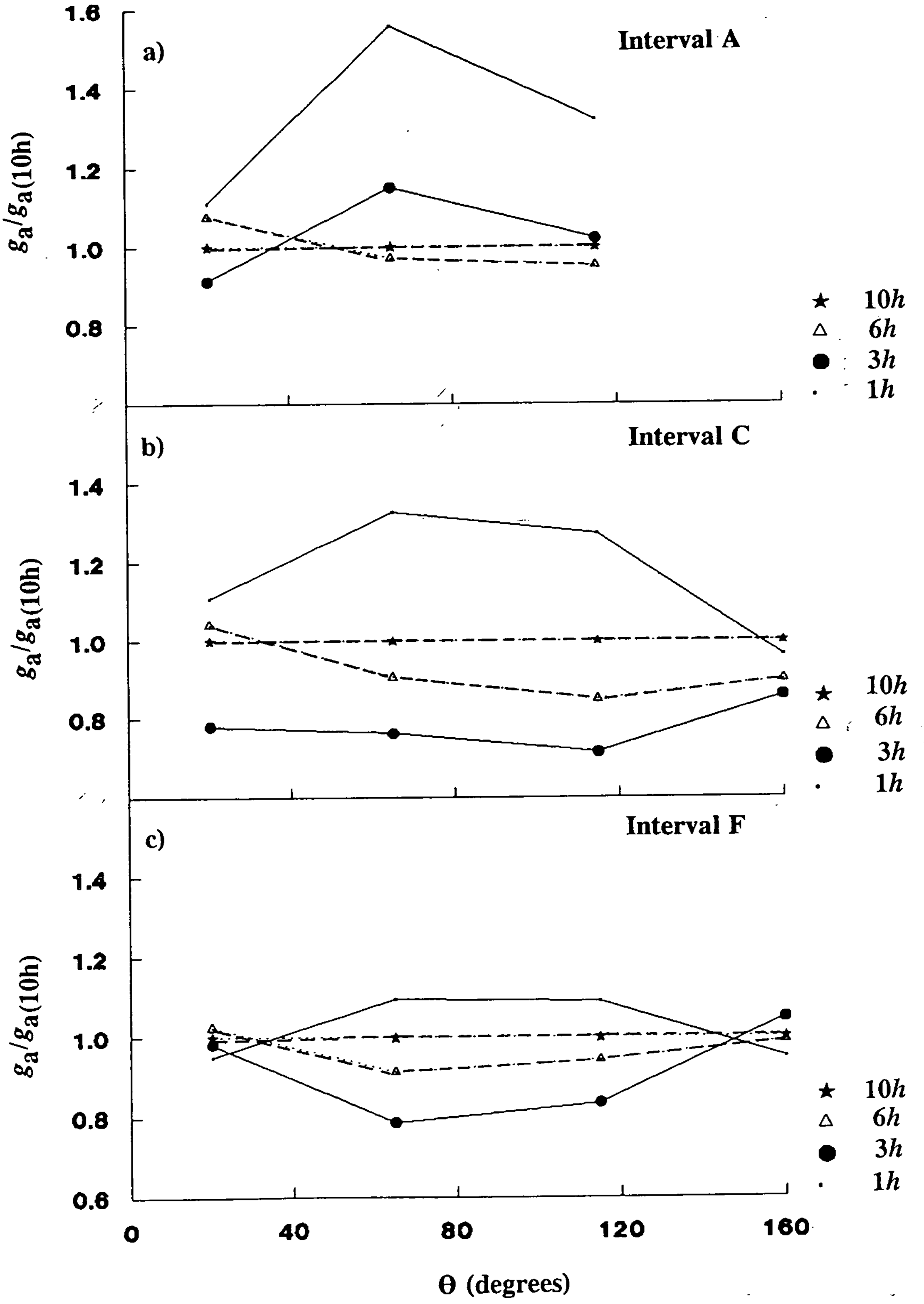


Figure 4.11 Change of normalized boundary layer conductance ($g_a/g_{a(10h)}$) with Θ for four distances behind a windbreak over the season. a) interval A, b) interval C and c) interval F.

corresponding $u/u_{(10h)}$.

4.2.6 Relationship between wind speed and boundary layer conductance

Data for each time period were edited to eliminate $u < 0.5$ m s^{-1}, since the starting speed of the anemometers was 0.45 m s^{-1}. Figures 4.12a - d, show the relationship between g_a and $\sqrt{u}$ for distances 1*h*, 3*h*, 6*h*, and 10*h* over the three time intervals A (.), B (+), and C (x).

A model of g_a against $\sqrt{u}$ for forced convection was fitted to the data for each position over each time interval (see eq. IV.12, Appendix IV). The resulting coefficients and standard errors are presented in Table 4.5.

Table 4.5 Coefficient *a* of the model $g_a = a\sqrt{(u)}$ for heated leaf replicas at four distances from the windbreak. s.e. represents 1 s.e.

Interval	1*h*	3*h*	6*h*	10*h*	Mean	s.e.
A	0.039	0.032	0.031	0.029	0.033	0.00062
B	0.036	0.030	0.031	0.035	0.033	0.00076
C	0.036	0.030	0.033	0.036	0.034	0.00081
E	0.029	0.029	0.031	0.033	0.031	0.00044
F	0.033	0.033	0.030	0.034	0.033	0.00038
Mean	0.035	0.031	0.031	0.033	0.033	0.00060

Interval D was excluded from the analysis since the values from 1*h* were in error. Average s.e. = 6.015×10^{-4}, so the 95% confidence interval (60 d.f.) for a mean estimate of *a* is 0.033 ± 0.0012 (m s^{-1})$^{0.5}$.

Equation IV.12, Appendix IV with appropriate values for the diffusion coefficient for heat in air (0.21 cm^2 s^{-1}), and the kinematic viscosity of air at 30 ^{o}C (0.16 cm^2 s^{-1}), gave a calculated value for coefficient *a* of 0.034. The coefficients shown in Table 4.5 vary around this figure with the model fitted for all the data having a value of *a* = 0.033. The model, using *a* = 0.034, was superimposed onto

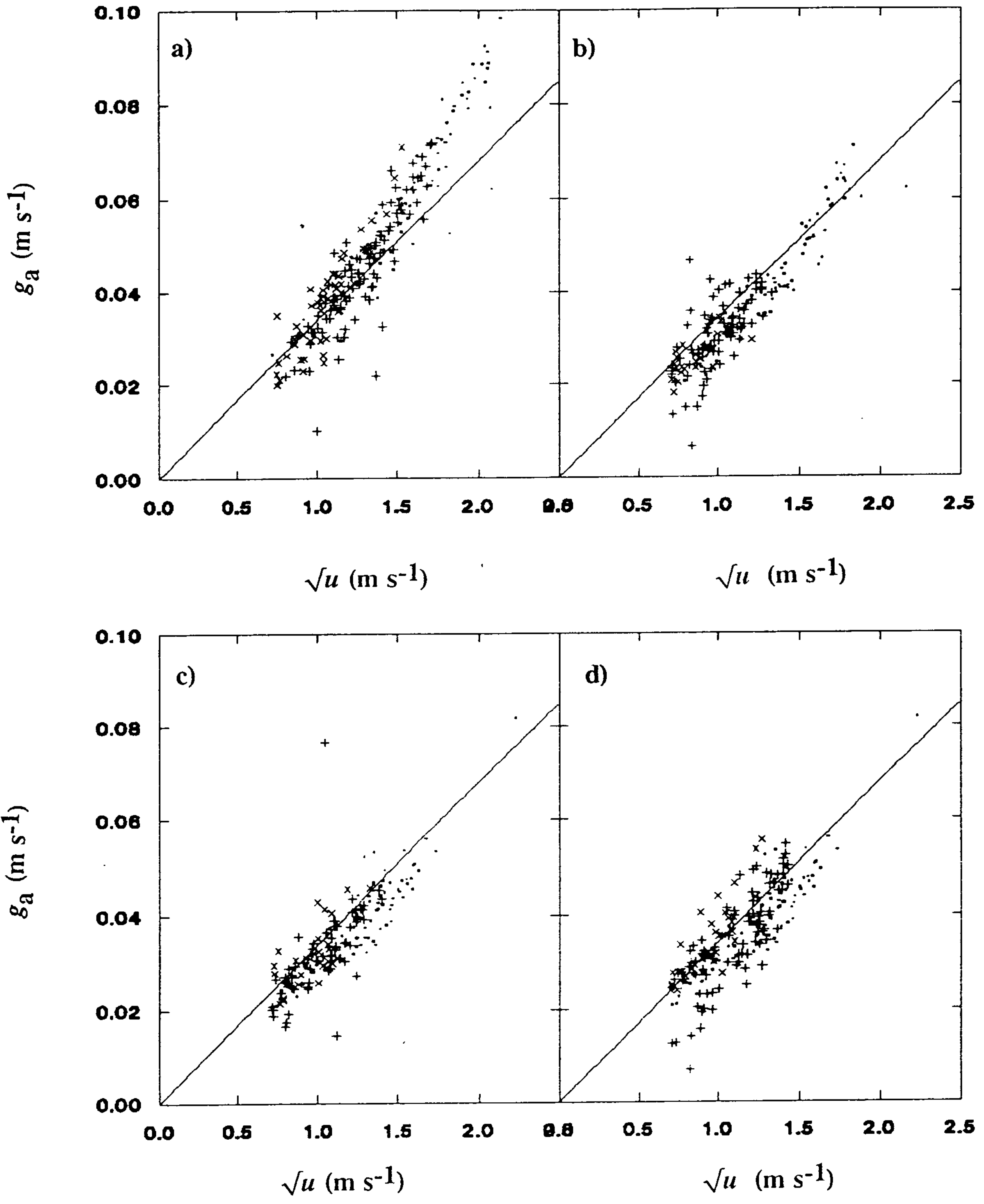


Figure 4.12 The relationship between boundary layer conductance (g_a) and $\sqrt{u}$ for a) 1*h*, b) 3*h*, c) 6*h* and d) 10*h*. For time intervals A (•), B (+), and C (×). The line indicates the relationship according to laminar flow theory.

Figures 4.12a - d.

The relationship outlined above is appropriate for $0.5 < u < 2.5$ m s^{-1}. The larger number of high wind speeds recorded at 1*h* are a reason for its apparently higher values of *a*. Appendix IV clearly shows that the laminar flow model for the heated replicas breaks down under wind tunnel conditions at $u > 3$ m s^{-1}, occurring at lower *u* under 'initially turbulent' conditions (see Appendix IV). When $u > 2.5$ m s^{-1}, g_a generally exceeded values predicted from laminar flow theory. A linear regression of g_a vs. *u* for $u > 2$ m s^{-1} gave an equation of the form $g_a = 0.017(u) + 0.016$, with an $r^2 = 0.69$ ($n = 48$), however a wider range of wind speeds would be required to derive a more accurate relationship at high wind speeds under turbulent conditions.

4.2.7 Effect of stability on normalised wind speed

Richardson numbers (Ri), calculated from configuration A at a distance of 6*h* from the windbreak on the windward side, were compared with u/u_o for data taken between days 240 - 248. The data were selected for $80^o < \Theta < 100^o$ when the crop was dry. There existed a tendency for u/u_o to increase with unstable conditions (more -ve Ri), but the relationship was not statistically significant at the 5 % level. A decrease of u/u_o with stable conditions was not noticeable. The range of stabilities varied between $-0.46 < h/L < 0.3$, ($-0.3 < \mathrm{Ri} < 0.1$). Conversion from Ri to *L* are taken from Monteith and Unsworth (1990), with (z - d) taken as 4 m, where *d* is zero plane displacement.

4.2.8 The change of boundary layer conductance with depth in canopy

Replicas were measured at three depths in the canopy, and five distances behind the windbreak, 1*h*, 3*h*, 6*h*, 10*h* and 16.7*h* (this distance was chosen since it was midway (100 m) between the windbreaks), but during the period of measurement at 10*h* (Table 3.4), rain and technical problems made values unreliable. The boundary layer conductances were normalized to the conductance at the top of the canopy (g_{ao} was at $z = h_c$).

Table 4.6 The change of g_a with depth in the canopy, for different distances from the windbreak. Daily means, s.e. represents 1 standard error.

Distance	height (m)	g_a ± s.e. (m s^{-1})	Normalized g_a ± s.e.
1*h*	1.8	0.0217 ± 0.0021	1
(n = 3)	1.2	0.0164 ± 0.0013	0.771 ± 0.017
	0.6	0.0141 ± 0.0007	0.680 ± 0.022
3*h*	1.8	0.0273 ± 0.0019	1
(n = 4)	1.2	0.0240 ± 0.0016	0.870 ± 0.016
	0.6	0.0227 ± 0.0019	0.834 ± 0.025
6*h*	1.8	0.0237 ± 0.0007	1
(n = 2)	1.2	0.0210 ± 0.0011	0.908 ± 0.040
	0.6	0.0180 ± 0.0003	0.798 ± 0.015
16.7*h*	1.8	0.0444 ± 0.0134	1
(n = 3)	1.2	0.0215 ± 0.0031	0.610 ± 0.034
	0.6	0.0225 ± 0.0057	0.592 ± 0.012
Mean	1.8	0.0243	1.0
(excluding	1.2	0.0205	0.84
16.7*h*)	0.6	0.0183	0.75

These measurements were taken late in the season when the canopy was well developed, earlier in the season ie. before 50 DAS, leaf area index was low and so the reduction of g_a with depth in the canopy may be substantially less than indicated in Table 4.6.

4.2.9 Comparison between unsheltered and windward sites.

Comparisons of wind speed at both crop height (h_c) and at 5 m were made between the two reference masts i) west of the windbreak, field 3a - 'windward' and ii) on the control, field 7b2 - 'unsheltered'.

'Windward' wind speeds at both 5 m and h_c were higher than 'unsheltered' with larger differences occurring at 5 m than h_c. Friction velocity, u_*, was calculated from wind speed at two heights, assuming $z_0 = 0.13h_c$, and $d = 0.63h_c$, (Monteith and Unsworth, 1990). Higher u_* was observed 'windward' on all compared days.

Table 4.7 Comparison of wind speed on the 'windward' ($u_{(w)}$) compared to 'unsheltered' ($u_{(us)}$); $u_{(w)} = a + b\,u_{(us)}$. s.e. represents 1 standard error.

Height	*a*	*b*	r^2	s.e.
5 m	-0.03	1.37	0.82	0.43
crop height	0.24	0.94	0.74	0.26

This relationship shows that $u_{(w)}$ at crop height was slightly higher for $u < 4$ m s^{-1} than $u_{(us)}$; $u_{(w)}$ at 5 m was substantially higher than $u_{(us)}$.

4.2.10 Effect of angle of incidence on optical porosity

A series of photographs were taken of the windbreak for $90^o < \Theta < 20^o$. These photographs were analysed using an image analysis system that calculated the ratio of gap to foliage. The ground was used as a lower limit of the windbreak and the upper limit of the windbreak was set by tracing round the uppermost leaves on the transparency; results are presented in Table 4.8.

Table 4.8 The optical porosity (ϕ) of the windbreak, taken from the analysis of photographs at different Θ.

Θ	ϕ	Θ	ϕ
90	0.27	50	0.15
80	0.23	40	0.16
70	0.23	30	0.15
60	0.19	20	0.11

The optical porosity of the windbreak decreased as Θ decreased from 90^o to 20^o, changing the windbreak from a medium to a dense windbreak. The windbreak consists of two sections; a high porosity section below the canopy $\phi = 0.63$ and low porosity section within the canopy $\phi = 0.12$.

4.3 DISCUSSION

4.3.1 Effect of incident wind velocity

It is often assumed that u/u_o is independent of u_o, however with the windbreak studied, the transition from u/u_o at low wind speeds to high wind speeds depended on height of measurement. For example at $z = 1$ m there was no change of u/u_o with u_o, whereas at $z = 3$ m change occurred quite abruptly at 2.8 m s^{-1} and 4.0 m s^{-1} in the open and dense windbreaks, respectively. The decrease of u/u_o of between 0.2 to 0.4 at high wind speeds was similar to that recorded for open windbreaks (Bates, 1911; Konstantinov and Struzer, 1965), although a sharp change of u/u_o between high to low wind speeds was not evident. Van Eimern *et al.* (1964) did show a sharp transition of u/u_o with u_o for a maple windbreak, at $x = 4h$ and $z = h/4$, occurring at $u_o = 5$ m s^{-1} but in this case u/u_o increased. The suggestion by Caborn (1957) that an increase in u_o would increase the turbulence of the incident air stream, and thus decrease the effectiveness of the windbreak was not observed here, possibly as a result of the turbulence set up by upwind windbreaks.

Most measurements taken over the season were below $z = h/2$ and with $u_o < 3$ m s^{-1}, so it was reasonable to take averages of u/u_o without including a parameter for dependence on u_o.

4.3.2 Effect of stability and roughness length

It has been suggested that any factor that increases the turbulence of the incident flow decreases the effectiveness of windbreak, ie. thermal instability or large roughness lengths. Initial measurements were taken at the beginning of the season when $h_c = 0.05$ m, whereas at the end of the season $h_c = 2.00$ m. If we take $z_o = 0.13h_c$, then z_o changed from 0.0065 m to 0.26 m over the cropping season, corresponding to h/z_o values of 923 and 23, respectively. A value of 0.007 m for

z_0 for a ridged soil given by McInnes *et al.* (1991) is similar to the value taken here. If all else remained constant, on this basis u/u_0 would be expected to rise over the season (Seginer, 1975a), but other more important factors such as ϕ may have swamped this effect..

The effect of thermal stability on u/u_0 found here was substantially less than has been quoted by other authors (Seginer, 1975a; Miller *et al.*, 1975; Jacobs, 1984). The thermal stratification may have been less ($-0.3 < Ri < 0.1$), than Miller *et al.* (1975) ($-1.97 < Ri < 0.13$), and Seginer (1975a) ($-1.4 < Ri < 0.2$). This may result from turbulence set up by the upwind windbreaks.

4.3.3 Effect of incident wind direction

A good fit to equation 4.3 was found for intervals C and D at $3h$ and $6h$ (r^2 of 0.91 to 0.98). The largest effect of Θ on u/u_0 was found at $3h$ and the least at $10h$, following the pattern found by Seginer (1975b). Values of b were much lower than those found by Seginer, the highest being 0.61 at $3h$ with negative values at $1h$. Seginer showed that b was sensitive to changes in z_0, so lower values of b may have resulted from the lower h/z_0 in this study (25) as compared to Seginer's study (83).

4.3.4 Effect of distance and time

The distance at which minimum u/u_0 occurred (x_{min}) depends on ϕ and z. Raine and Stevenson (1977) showed for artificial barriers of high porosity ($\phi = 0.5$) $x_{min} = 6h$, whereas for lower porosity barriers ($\phi = 0.2$) $x_{min} = 3h$. Nageli (1946) also showed that, whereas with medium porosity windbreaks $x_{min} = 5h$, low porosity windbreaks had an $x_{min} = 2h$.

At the beginning of the season the porosity of the windbreak was high (0.63) near the ground where the measurements were made and $x_{min} = 6h$. As the season progressed x_{min} moved towards $3h$ where it remained until the end of the season. This movement of x_{min} may in part be attributable to closing the gap below the canopy by millet plants on the windward side of the windbreak. Average height of the gap below the canopy was 1.59 ± 0.08 m. The millet height over interval C was 0.70 to 1.00 m. So growth of the windward millet would have made a contribution to reducing the porosity of the lower half of the windbreak.

As Θ increased up to 90° the optical and probably the effective porosity increased since the path length of the wind through the trees decreased (Section 4.2.10), in contrast to vertical slat fences for which ϕ would decrease. Konstantinov and Struzer (1965) have shown that for high ϕ windbreaks, efficiency may not be maximal at $\Theta = 90^{\circ}$. The effectiveness of a windbreak over a distance of 15*h* in its lee (E_{15}), can be calculated by weighting the u/u_0 at each distance by the area it represents. This trial showed that during intervals A and B, E_{15} was maximal when $\Theta = 30^{\circ}$. During intervals C and D maximum E_{15} was when $\Theta = 90^{\circ}$ and during interval E maximum E_{15} was when $\Theta = 65^{\circ}$. The pattern of these results are very similar to those found by Konstantinov and Struzer (1965) who found maximum effectiveness of windbreaks with ϕ of 0.8, 0.6, and 0.3 at Θ of 30°, 60° and 90°, respectively. However, the actual values of porosity are much lower than those given by Konstatinov and Struzer (1965), changing from 0.27 to 0.12 over the season. Taking the change of ϕ of the lower half of the windbreak over the season (0.63 to 0.12) suggests that the porosity of the lower half of the windbreak is much more important in determining the overall effectiveness of the windbreak than the upper half.

The increase in wind speed at 1*h* has not been reported in many studies, probably because this does not occur with artificial barriers of uniform porosity or in well designed windbreaks, although reports of high wind speeds through gaps in windbreaks are well documented (Van Eimern *et al.*, 1964; Heisler and Dewalle, 1988). The increase in u/u_0 at 1*h*, exceeding 1.0 and peaking when $\Theta = 90^{\circ}$, supported the idea that air preferentially flowed under the trees. The magnitude of this effect decreased over the season since the ϕ of the lower part of the windbreak decreased.

The change of measurement height with crop growth over the season may also make a difference to u/u_0. Figure 4.8 shows that u/u_0 at 3*h* was larger than u/u_0 at 6*h* at $z = 1$ m, whereas at $z = 3$ m the pattern was reversed. Bean *et al.* (1975) suggested that measurements made near the ground could be made at any height without affecting u/u_o. Raine and Stevenson's data (1977) supported this for heights below $z = h/3$, although all these measurements were for uniform porosity with height and no crop. The information from Figures 4.8 and 4.9 suggested that the height of measurement had an important effect on u/u_o.

4.3.5 Boundary layer conductance

The relationship between g_a and u was not dissimilar to that expected from laminar flow theory for forced convection, for $0.5 < u < 2.5$ m s^{-1} and the pattern of $g_a/g_{a(10h)}$ was similar to that of $u/u_{(10h)}$ behind a windbreak.

Values of g_a found here fall within the range found by Azam-Ali (1983) of 0.008 - 0.04 m s^{-1} for millet leaf replicas made out of blotting paper. Average normalized g_a for a leaf up to a distance $8h$ behind the windbreak was 0.84 at $z = 0.67h_c$, and 0.75 at $z = 0.33h_c$. Assuming that g_a for a leaf is proportional to $\sqrt{u}$ (eq. IV.12), at $z = 0.67h_c$ u normalized to the top of the canopy would be 0.70. This is high compared to normalized wind speed at $z = 0.64h_c$ of 0.21 measured within a wheat canopy (Baines, 1972). Millet canopies are open and so smaller reductions in u with depth in the canopy would be expected. The setting up air vortices between hills of millet plants, as demonstrated in sorghum by Arkin and Perrier (1974), may also contributed to the smaller wind speed gradient within the canopy. The high value of g_a at $16.7h$ coincided with higher wind speeds found towards the centre of the field (Figure 4.10a).

4.3.6 Wind variability

The highest wind variabilities were found at tree top height in the windbreak ($z = h$, $x = 0$) and at ground level at $10h$ ($z = 0$, $x = 10h$) (Figure 4.10b). High wind variability at $6h$ and $10h$ was especially noticeable in the middle of the season (Figure 4.6), and coincided with the minimum porosity of the windbreak-millet system. Raine (1974), Raine and Stevenson (1977) and Perera (1981) showed decreasing porosity increased turbulence in the wake zone and lowest turbulence intensities occurred at $3h$. McNaughton (1988) described a triangular quiet zone extending up to $x = 7h$ to $8h$. Measurements here suggest that the wake zone starts between $8h$ and $10h$.

4.3.7 'Windward' verses 'unsheltered'

Lower wind speeds were recorded at both crop height and 5 m on 'unsheltered' as compared to 'windward'. This result was unexpected and emphasises the problems with comparing microclimatic comparisons inside and outside the windbreak system. Wind speeds at crop height were on average 9.5 % lower in the unsheltered field compared to the windward field. The reasons for this are unsure, the increase in turbulence set up by the first windbreak in the system could have increased the wind speed, or possibly the incident wind of the two sites was different. Problems of this sort have been experienced in other field comparisons (Rollin, 1983; Nageli, 1946).

4.4 SUMMARY OF RESULTS

1) Maximum shelter at the start of the season occurred at 6*h* behind the windbreak, and moved towards 3*h* by the middle of the season, because of the change in porosity of the windbreak caused by the growth of the millet.

2) A quite zone existed from 2*h* to ca. 8*h* with increasing wind variability from 8*h* to 15*h*. Higher wind variability occurred towards the middle of the season, caused by a decrease in the porosity of the windbreak.

3) u/u_o was independent of u_o at a height of $z = 1$ m, whereas at $z = 3$ m, u/u_o decreased at high u_o.

4) In the middle of the season, u/u_o was linearly related to $(1 - \sin \Theta)$.

5) u/u_o at $x = 1h$ and $z = h_c$ exceeded 1.0 at $\Theta = 90^o$ because of preferential air flow under the trees, but was lower than at other distances behind the windbreak when $\Theta = 0^o$, resulting from momentum absorption by the windbreak.

6) Boundary layer conductances of millet leaves for $0.5 < u < 2.5$ m s^{-1} were similar to those predicted from laminar boundary layer theory.

CHAPTER 5

THE EFFECT OF WINDBREAKS ON PLANT ENERGY BALANCE

5.1 INTRODUCTION - REVIEW OF THE EFFECTS OF WINDBREAKS ON PLANT GROWTH

Windbreaks can change the amount of radiation absorbed by a plant, its boundary layer conductance and hence its energy balance (eq. 1.2). Chapter 4 describes changes in wind speed and turbulence behind a windbreak and its effect on boundary layer conductance. Chapter 5 shows how this affects millet transpiration, stomatal conductance, leaf temperature and growth.

5.1.1 Effects of shading

Shading of crops by adjacent trees depends upon extent of the canopy, leaf area, and leaf angle. Extensive reviews of the light interception by canopies are given by Russell *et al.* (1989) and in agroforestry systems by Jackson (1989). Reduction in solar radiation (S_t) causes a reduction in photosynthetically active radiation (R_{par}) where;

$$R_{par} \approx 0.5S_t \qquad (5.1)$$

Growth of vegetation is proportional to the quantum flux density (Q), which is related to S_t;

$$Q \approx 2.1S_t \qquad (5.2)$$

Where Q is in μmol m^{-2} s^{-1}, and S_t is in W m^{-2} (Monteith and Unsworth, 1990). The reduction in Q is a major cause of the yield reduction observed near the windbreak.

S_t is also the major day time component of R_n (equation 5.3);

$$R_{\mathrm{n}} = S_{\mathrm{t}}(1 - \alpha) + L_{\mathrm{d}} - L_{\mathrm{u}} \tag{5.3}$$

where L_{d} and L_{u} are the downward and upward fluxes of long-wave radiation, respectively. Many workers (Bates, 1911; Van Eimern *et al.*, 1964; Jackson, 1989) have shown that orientation of windbreaks affects shading, with the magnitude of shading changing with solar angle. North - south windbreaks give symmetrical shading on both sides of the windbreak, whereas east - west windbreaks will shade one side more than the other depending on the relative position of the sun. Van Eimern *et al.* (1964) suggest that there may be an increase in short-wave reflected radiation on the sunny side of the belt, although this has not been widely reported and is probably small.

5.1.2 Effect of shelter on air temperature

Aslyng (1958) found that mean sheltered midday temperatures were 1.6 °C and 0.8 °C higher than in an open field, at $x = 4h$ and $8h$, respectively, with lower night-time temperatures at $x = 4h$. Bates (1911) reported a mean 2.2 °C rise on sunny days in sheltered zones, whereas he considered lower night-time temperatures in shelter could be a major problem for fruit growers. Brown and Rosenberg (1972) reported that mean day-time temperatures were 1.8 °C higher behind a maize windbreak, and Ujah and Adeoye (1984) found increases in mean maximum air temperature of between 0.9 and 1.8 °C at $x = 2h$ behind a Eucalyptus windbreak compared to open farm land in Nigeria. Long and Persaud (1988) reported no significant difference in maximum temperatures between sheltered and open areas behind a double row neem windbreak in Niger, although minimum temperatures in the sheltered areas were 1.2 °C lower. General agreement emerges that during the day shelter increases air temperature and at night often decreases air temperature, day-time temperature increases usually exceed night-time decreases.

5.1.3 Effects of shelter on leaf and soil temperature

Effects of shelter on air temperatures are largely of interest only in default of good measurements of plant tissue temperatures and soil temperatures (MacKerron and Waister, 1985).

5.1.3.1 Soil temperatures and shelter

Day-time soil temperatures are generally higher in shelter. Van Eimern *et al.* (1964) reported mean day-time increases in soil temperatures of 1 ^{o}C in shelter at 5 cm depth, similar to maximum differences in soil temperature found by Ujah and Adeoye (1984). Differences closer to the surface would probably be larger, and surface soil temperatures may exceed those optimal for plant growth, soil temperatures at 0.5 cm in bare soil in Niger often exceed 50 ^{o}C, (Wallace *et al.*, 1989).

5.1.3.2 Effect of plant and soil temperature on millet growth

Many developmental processes are temperature controlled with their rate increasing linearly above a base temperature and varying little between processes (ODA, 1987a; Grace, 1988b). Millet germination increased linearly with soil temperature from 10 - 12 ^{o}C to an optimum temperature of 32 - 33 ^{o}C (Tg_{opt}), then decreasing linearly to a lethal temperature of around 48 ^{o}C (ODA 1987a). Van Den Beldt (personal communication) suggested that one of the major causes of improved millet growth under a canopy of *Faidherbia albida* was reduction of soil temperatures at the beginning of the season, as a result of shading of the soil by the tree canopy. Soil temperature affects germination and early growth of millet, since the meristem remains below ground level for the first 3 weeks of plant development (Ong, 1983a; Corlett, 1989).

Optimum temperature for many millet growth processes is between 30 ^{o}C to 32 ^{o}C. Millet leaf extension was found to be maximum at midday and corresponded well to the meristem temperatures, with the rate of expansion decreasing above 32 ^{o}C (Ong, 1983c). This type of response has been noted with many cereals (Terry *et al.*, 1983). However, optimum temperatures for grain yields and tillering are lower between 20 ^{o}C and 27 ^{o}C (Fussell *et al.*, 1980; Ong and Monteith, 1985; ODA, 1987a). Temperature also affects the duration of the growth stages, so that advantages of faster rates of increase may be offset by shorter durations of that growth stage (Ong and Monteith, 1985).

5.1.4 Effects of shelter on humidity

Rosenberg *et al.* (1983) showed that over a sugar beet crop (z = 0.5 m), on sunny days the vapour pressure of the air (e_a) was higher behind a maize windbreak than an open field with maximum differences occurring at 6*h* during the middle of the day; whereas on cloudy days the effect was negligible. Brown and Rosenberg (1972) measured a 0.6 kPa increase in e_a 0.25 m above a sheltered sugar beet crop, whereas Carr (1985) reported a much smaller difference in e_a of 0.06 kPa 0.15 cm above a sheltered tea canopy in Kenya. Aslyng (1958) measured an increase in e_a ($z = 0.5$ m) over pasture, however the increase in temperature meant that day-time saturated vapour pressure deficit of the air (D_a) increased by 0.23 kPa relative to the unsheltered field. Long and Persaud (1988) reported a mean increase of 5 % relative humidity over the season within a sheltered millet crop in Niger. These data indicate that an increase in e_a is expected in shelter although the magnitude varies with environmental conditions and underlying vegetation. D_a may increase or decrease in shelter depending on the increase in temperature.

5.1.5 Effects of shelter on stomatal and cuticular conductance

5.1.5.1 Cuticular conductance

Increases in total leaf conductance at high wind speed generally result from an increase in leaf cuticular conductance, as a consequence of leaf damage. The rubbing of *Festuca arundinacea* leaves, (Grace, 1974) and damage of various tree leaves at high wind speeds (Dixon and Grace, 1984) has been shown experimentally to increase cuticular conductances. However, not all species are sensitive to damage at high wind speeds, for example no significant increase in g_c was measured with Sitka spruce (*Picea sitchensis*) needles exposed to high wind speeds (Grace *et al.*, 1975). Abrasion by sand particles in high winds causes increases in cuticular conductance (Armbrust, 1984) and may well account for most damage to leaf cuticles in the field.

5.1.5.2 Stomatal conductance

Response of g_s to S_t and Q : Linear increases in g_s were observed in millet with increases in S_t (Squire and Black, 1981; Henson *et al.*, 1982), with differing responses for the adaxial and abaxial surfaces. The response of g_s to Q reaches a maximum, (g_{smax}) at a quantum flux density Q_{sat} (Jarvis and Morison, 1981).

Although highly complex models are available for prediction of stomatal conductance (Collatz *et al.*, 1991), simple relationships may also be used such as given in eqs. 5.4a and b;

$$\text{if } Q < Q_{\mathrm{sat}} \qquad g_{\mathrm{s}} = g_{\mathrm{smax}} - b_{\mathrm{q}}(Q_{\mathrm{sat}} - Q) \tag{5.4a}$$

$$\text{if } Q => Q_{\mathrm{sat}} \qquad g_{\mathrm{s}} = g_{\mathrm{smax}} \tag{5.4b}$$

where b_{q} is the sensitivity of the plant to decreases in Q.

Response of g_{s} to u and D_{a} : If the effects of wind on g_{c} are separated from g_{s}, most work shows a decrease in g_{s} with increasing u although increases in g_{s} with wind speed in grasses have occurred, as a result of damage to guard cells (Grace, 1974). Decreases in g_{s} with increasing D_{a} have been reported for many species (Lösch and Tenhunen, 1981), including millet (Squire, 1979; Henson *et al.*, 1982). In both field and glasshouse g_{s} decreased linearly with increasing D_{a}, the largest responses occurring at high S_{t} (Black and Squire, 1979). Squire (1979) suggested that the response to D_{a} only existed for well-watered plants, although this was not found by Henson *et al.* (1982). Grace (1977) raised the question of whether the stomata respond directly to u, or to changes in vapour pressure deficit at the surface of the leaf (D_{surf}). Aphalo and Jarvis (1991) used the equation 5.5,

$$g_{\mathrm{s}} = g_{\mathrm{smax}} - b_{\mathrm{d}}(D_{\mathrm{surf}}) \tag{5.5}$$

where b_{d} is the sensitivity of the plant to changes in D_{surf}. A change in boundary layer conductance will change D_{surf} (Grace *et al.*, 1975; Bunce, 1985), using equation 5.6;

$$D_{\mathrm{surf}} = e^{*}_{(\mathrm{Tl})} - e_{\mathrm{surf}} \tag{5.6}$$

and;

$$e_{\mathrm{surf}} = e_{\mathrm{a}} + (e^{*}_{(\mathrm{Tl})} - e_{\mathrm{a}})\, g_{\mathrm{leaf}}/g_{\mathrm{a}} \tag{5.7}$$

where e_{surf} is the vapour pressure at the surface of the leaf and $e^{*}_{(\mathrm{Tl})}$ is the saturated vapour pressure at the temperature of the leaf, g_{leaf} is as defined in eq 1.3, and includes g_{a}, g_{s} and g_{c}.

Effect of shelter on g_s - Field measurements : Higher values of g_s were reported for sheltered bean leaves (Rosenberg, 1966), turnips and sugar beet plants (Marshall, 1974) and wheat (Skidmore *et al.*, 1974). Frank and Willis (1972) and Frank *et al.* (1974) found higher g_s in sheltered wheat and soybeans under irrigation, whereas under dry-land conditions the conductances were lower in shelter. Radke and Hagstrom (1973) found that sheltered soybeans showed significantly higher stomatal conductances in the morning, but showed lower conductances in the afternoon than unsheltered soybeans. Carr (1985) found higher g_s for tea in shelter during the wet season in shelter but no differences in the dry season, the changes being attributed to differences in D_a and plant water status, and not Q.

5.1.6 Effects of shelter on evaporation

The Penman formula (Penman, 1948) indicates a reduction of evaporation with a reduction in wind speed. Experiments using evaporation pans and piche evaporometers behind windbreaks support this. Nageli (1946) (cited by Van Eimern *et al.*, 1964), found that evaporation from a clay evaporometer was proportional to the square root of the wind speed. Bates (1911) reported savings in water of between 10 to 30 % behind a range of windbreaks. Decreases of 23 % in pan evaporation were reported over the season in Niger by Long and Persuad (1988) and annual reductions of 44 % and 23 % in evaporation at $x = 4h$ and $8h$ were calculated by Aslyng (1958) from the Penman equation. Windbreaks are most effective in reducing evaporation in situations where advection is dominant (Lomas and Schlesinger, 1970; Rosenberg *et al.*, 1983).

Evaporation from a soil surface depends upon the wetness and temperature of the soil surface and vegetation cover. Under dry conditions, the effect of shelter in reducing soil evaporation may be small, but under irrigated conditions, with regular wetting of the soil surface, reductions are likely to be much larger. Aase and Siddoway (1976) found that soil behind a perennial grass barrier remained wetter for up to three days after irrigation when compared with unsheltered conditions.

5.1.7 Effect of shelter on plant transpiration

Equation 1.2 indicates that transpiration per unit leaf area, may increase or decrease as a result of increasing wind speed (Section 1.3.2.2), depending on the relative sizes of g_{leaf} and g_{a}. Dixon and Grace (1984) showed that in three tree species transpiration rates decreased with increasing wind speed resulting from a reduction of the leaf to air vapour pressure difference as a consequence of reduced leaf temperature.

Few direct measurements of transpiration have been made behind windbreaks. Miller *et al.* (1983) measured transpiration of a 1 m high irrigated soybean crop using a lysimeter. By using a moveable fence they managed to eliminate the effects of increased leaf area in shelter (Section 2.1.3), and calculated that shelter reduced transpiration by 20 %. The water saving being most important when sensible heat advection was large. Radke and Hagstrom (1973) also measured transpiration directly with a potometer and found that while the soybeans were well watered stomatal conductance increased in shelter and transpiration decreased. Whereas when plants were stressed, at first stomatal conductance and transpiration increased in shelter and then stomatal conductance decreased but transpiration increased. So under well-watered conditions transpiration does apparently decrease in shelter, however under stressed conditions the situation is more complex.

Shelter may cause an increase in leaf area as well as an increase in transpiration per unit leaf area. So a sheltered crop may deplete water reserves earlier than an unsheltered crop which, in a water-limited environment, may cause the sheltered crop to become stressed while unsheltered plants remain unstressed (Jensen, 1954; Grace, 1988a). Alternatively the rapid early growth of sheltered plants may stimulate increased rooting enabling plants to access a greater soil volume, increasing the availability of water and nutrients (Stoeckler, 1962). Thus, the possible consequences of shelter for water use are several and difficult to predict.

5.2 RESULTS AND DISCUSSION

The results section is divided into six parts; i) the relationship between energy fluxes within the windbreak system; ii) the change of radiation with distance from the windbreak; iii) changes in air and leaf temperatures and humidity with distance from the windbreak; iv) calculation of the solar radiation conversion coefficient for millet over the season; v) changes of stomatal conductance and vapour pressure at the surface of the leaf with distance from the windbreak and its relation to solar radiation conversion coefficient; and vi) calculation of leaf transpiration using micrometeorological measurements and leaf temperatures and the Penman-Monteith equation, and evaporation using the Penman equation for millet behind the windbreak.

5.2.1 Energy fluxes

5.2.1.1 Relationship between solar and net radiation

The relationship between day-time R_n and S_t (eq 5.3) may be rewritten in the form;

$$R_n = a_r + b_r S_t \tag{5.8}$$

where a_r corresponds to the longwave radiation loss (L_d - L_u) and b_r corresponds to (1 - α) (Monteith and Szeicz, 1961). a_r changes with radiative temperature of the underlying surface, and α with solar elevation (Monteith and Szeicz, 1961). The calculated regression (eq 5.8) on most days showed significant linearity ($r^2 > 0.95$), with 56 % of days having $r^2 > 0.99$. Figure 5.1a shows the relationship between R_n and S_t at 16 DAS (start of the season) and 75 DAS (maximum leaf area). Hysteresis resulted from higher surface temperatures, therefore higher L_u in the afternoon than morning for the same value of S_t, and may be larger over bare soil than a crop (Monteith and Szeicz, 1961), although that was not apparent here.

b_r was between 0.6 - 0.8 and increased slightly over the growing season (Figure 5.1b), ie. α decreased from 0.4 to 0.2. Allen *et al.* (1990) measured solar reflectivity over bare sandy soil in Niger of between 0.35 to 0.41 which decreased to 0.3 over a millet crop, very similar to the values found here. Soil solar reflectivity ranges from 0.05 for wet clays to 0.40 for dry sands (Oke, 1987). Monteith (1959) working with a wet clay reported that exposure of the soil decreased α, whereas exposed soil in this case (dry sand) increased α above that for a full canopy. The decrease in α as the season progressed can be attributed to an increase in leaf area and ground cover. At maximum leaf area, average α over 7 days was 0.26 agreeing with Monteith's (1959) suggestion that α = 0.25 for many

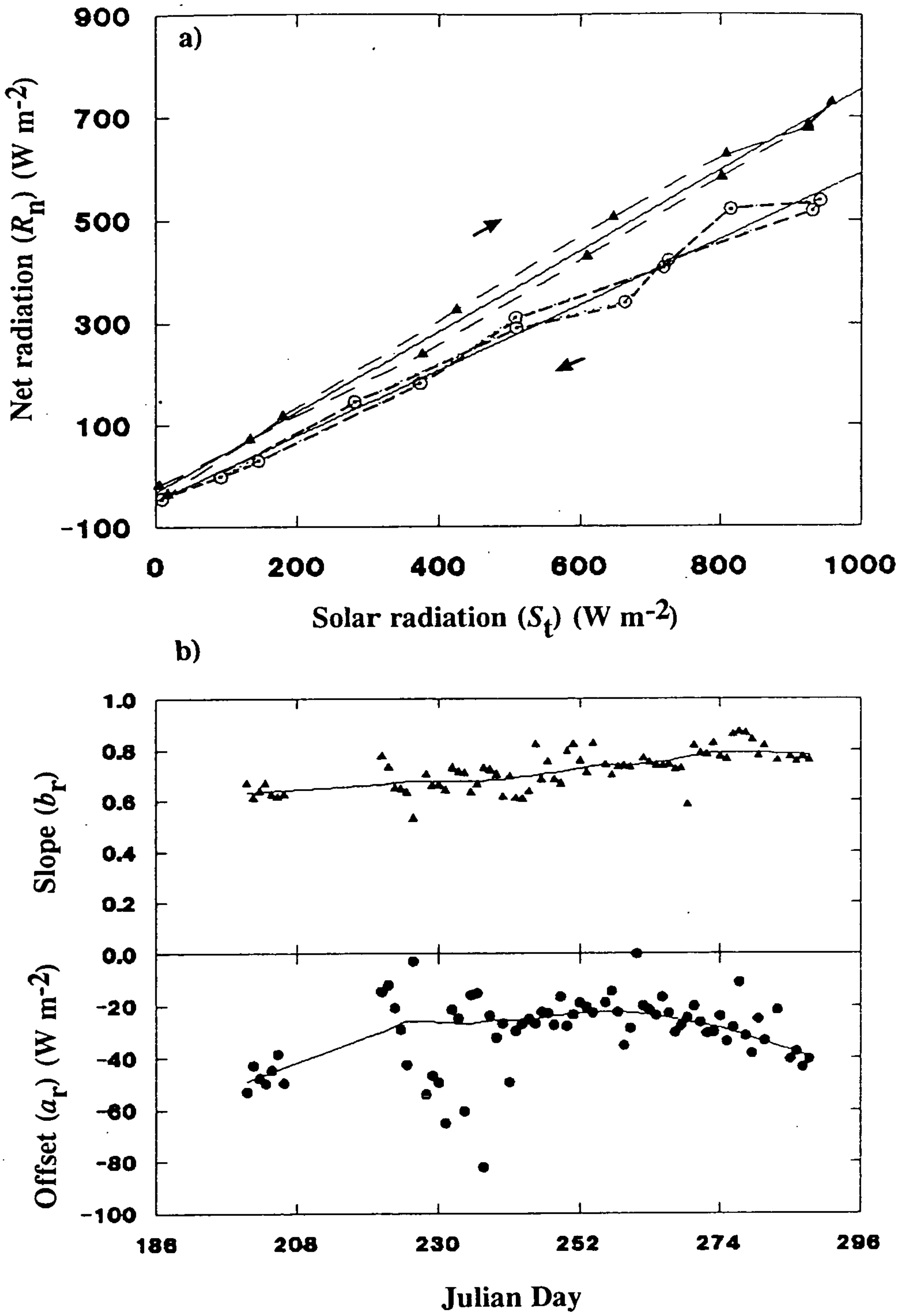


Figure 5.1 a) Relationship between S_t and R_n over a millet crop when $S_t > 0$ W m^{-2} for two days in 1989. Day 202 (o) at the beginning of the season, and Day 261 (▲) at maximum L. The arrow indicates the chronological sequence of measurements. b) Slope b_r and offset a_r of eq. 5.8 $R_n = a_r + b_r S_t$, between Julian day 186 and day 293 in 1989. Line indicates a moving average, using 40 % of the values.

crops at canopy cover. α decreased towards the end of the rainy season to 0.20 ± 0.1 (n = 16), despite lower leaf areas (Chapter 2). Stanhill (1981) quoted α of around 0.20 in tropical semi-arid systems for wheat, cotton and maize, resulting from high sun angle and sparse crops, also the increase in crop height may have reduced α (Oke, 1987).

a_r corresponds to the difference in longwave radiation when $S_t = 0$. The maximum over the middle of the season of -20 W m^{-2} (Figure 5.1c), was 26 W m^{-2} higher than at the start of the season, and 14 W m^{-2} higher than the end of the season. This suggested that radiative temperature differences between the surface and the air were higher and start and end of the season than middle, which is supported by actual temperature measurements (Section 5.2.3). Changes in a_r cannot be accounted for by changes in surface emissivity ie. from soil (0.92) to leaf (0.98), (Wright, 1990), because the change in a_r was in the opposite direction to what would be expected by an increase in emissivity. Quoted values of a_r for a variety of surfaces of between 90 and 120 W m^{-2} (Rosenberg *et al.*, 1983), exceeded values found here. Values of a_r of between 50 to 80 W m^{-2} (Monteith and Sziecz, 1961; 1962), were similar to those found here but were calculated taking into account the heating coefficient. This was not possible here because of the need to have independent measurement of α. The seasonal average for eq. 5.8 was $R_n = 0.71S_t - 30.6$.

5.2.1.2 Relationship between net radiation and ground heat flux

The relationship between ground heat flux G_s and R_n is given below;

$$G_s = a_g + b_g R_n \qquad (5.9)$$

where a_g and b_g are calculated daily coefficients. b_g decreased from 0.4 at the beginning of the season (bare soil) to 0.1 (maximum L) (Figures 5.2a - b), increasing as L decreased towards the end of the season. b_g varies with soil water content and canopy cover, both which increase towards the middle of the season. A wet loam had b_g of 0.22 and substantial hysteresis, whereas when dry $b_g = 0.50$, (Rosenberg *et al.*, 1983), covering the range found here. $G_s = 0.4R_n$ at the start of the season, decreasing to 0.1 to $0.2R_n$ at maximum L, similar to Wallace *et al.*

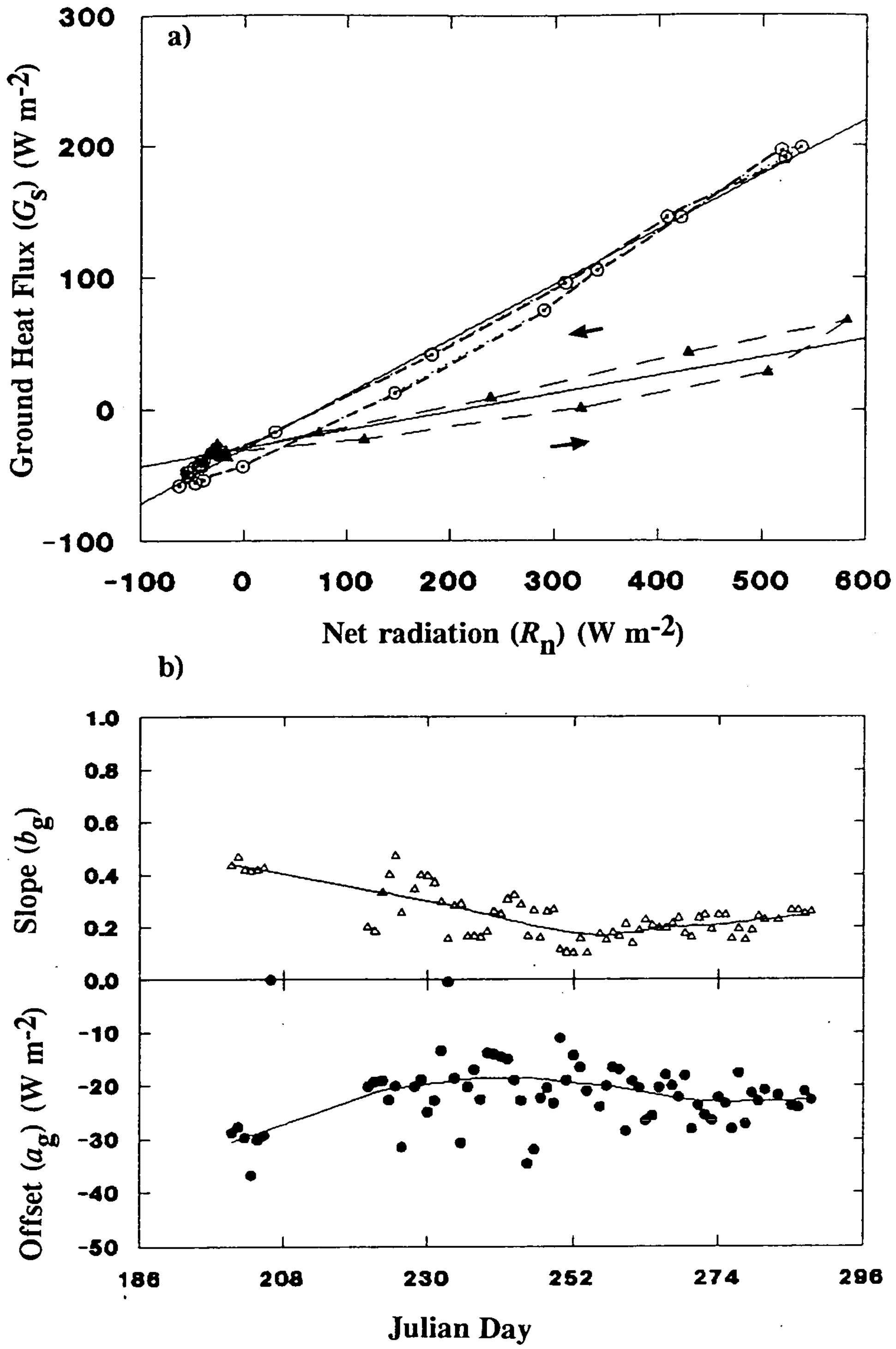


Figure 5.2 a) Relationship between R_n and G_s, for a millet crop for 2 days in 1989. Day 202 (o), and day 261 (▲). The arrow indicates the chronological sequence of measurements. b) Slope b_g and offset a_g of eq. 5.9 $G_s = a_g + b_g R_n$, between Julian day 186 and 293. Line indicates a moving average, using 40 % of the values.

(1986) for the same soil, although slightly higher than expected under many cropping systems (Monteith, 1976), because of the low vegetation cover. The seasonal average for eq. 5.9 was $G_s = 0.24R_n - 21.8$.

5.2.1.3 Daily totals

Total daily solar, net radiation and ground heat flux over the growing season between day 196 and 293 are shown in Figure 5.3. Average daily total S_t for 1989 was 20.39 MJ m^{-2} d^{-1}. On rainy days values decreased to around 7 MJ m^{-2} d^{-1}, but on 70 % of days total S_t was between 20 and 25 MJ m^{-2} d^{-1}. Total daily net radiation increased from 10 MJ m^{-2} d^{-1} to 15 MJ m^{-2} d^{-1} as the season progressed, with a seasonal average of 11.74 MJ m^{-2} d^{-1}. Seasonal average of total daily ground heat flux was 0.9228 MJ m^{-2} d^{-1}.

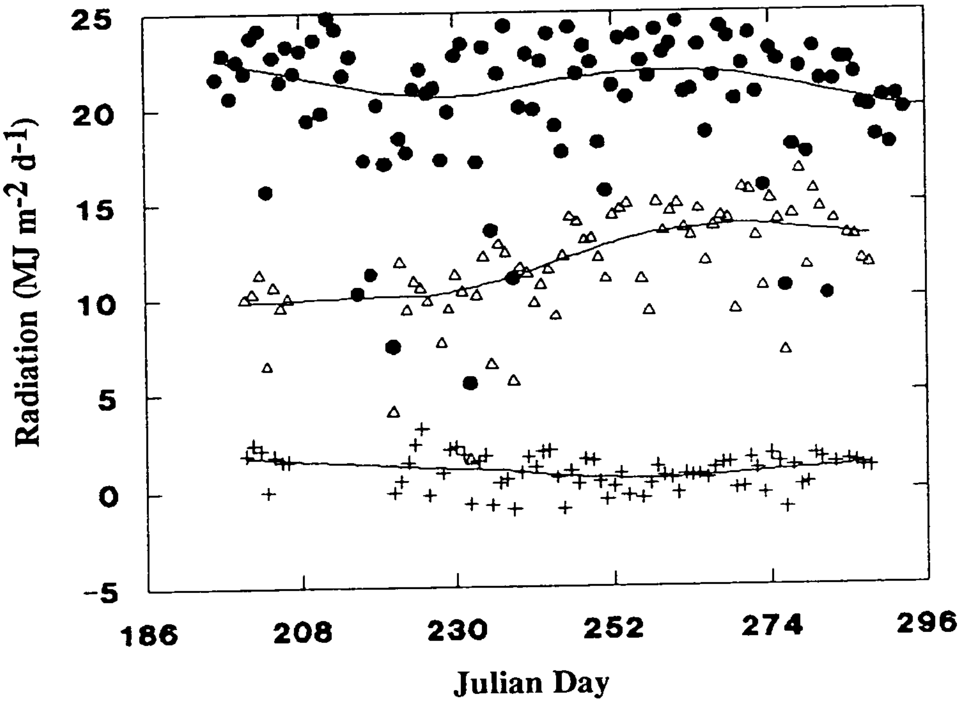


Figure 5.3 Total daily values of solar radiation (S_t) (●), net radiation (R_n) (△), and ground heat flux (G_s) (+), over 1989 cropping season. Lines are moving averages, using 40 % of the values.

5.2.2 Change of radiation with distance from the windbreak

5.2.2.1 Solar radiation

Nine transects of solar radiation under the windbreak canopy were measured at different positions normal to the windbreak when no crop was present (Configuration E; Section 3.3.5). The proportion of solar radiation reaching the ground (transmissivity, t_s) changed with distance from the windbreak and time of day (Figure 5.4). Significant shading beyond 1*h* only occurred at the end of the day. Lowest daily t_s (0.6) was directly beneath the trees, (Figure 5.5), with t_s < 0.9 only occurring within the zone ± 5.5 m. The effect of the reduction of S_t near the windbreak on PAR and crop growth is discussed further in Chapter 7.

5.2.2.2 Net Radiation

Maximum decreases in R_n at 1*h* relative to 10*h* occurred at 17.00 h (Figure 5.6), corresponding to the reduction of S_t (Figure 5.4e). Over these 2 hours R_n at 1*h* was 0.675 MJ m^{-2} less than 10*h*. Day-time total R_n was 14.43 MJ m^{-2}, ie the reduction in R_n at 1*h* was 4.7 %. R_n was slightly larger at 1*h* than 10*h* in the middle of the day (Figure 5.6), which may have resulted from lower surface temperatures at 1*h*, or reflected solar radiation from the windbreak, and accounted for +0.444 MJ m^{-2}. So the reduction summed over the day may have been 0.231 MJ m^{-2}, or 1.6 % of day-time total. At 3*h*, total reduction in R_n relative to 10*h* was 0.04 MJ m^{-2}, ie. negligible.

R_n was significantly reduced only in the late afternoon at a distance of 1*h* from the windbreak, so for the purpose of energy balance calculations net and solar radiation can be assumed to be uniform over the windbreak field for most of the day. The reduction of air and leaf temperatures near the windbreak (Section 5.2.3), cannot then be attributed to lower R_n, but to higher wind speeds at 1*h* (Section 4.2.1).

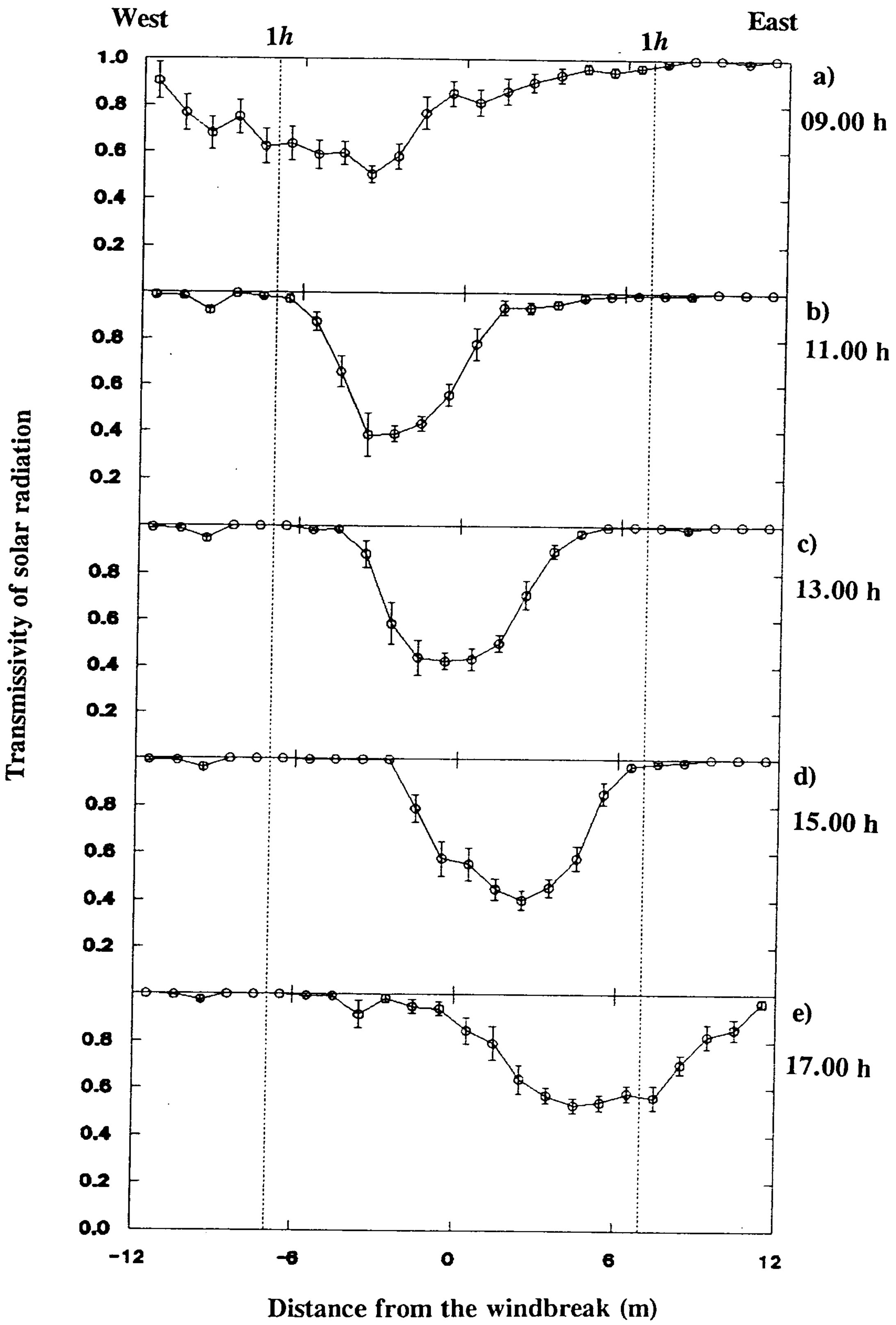
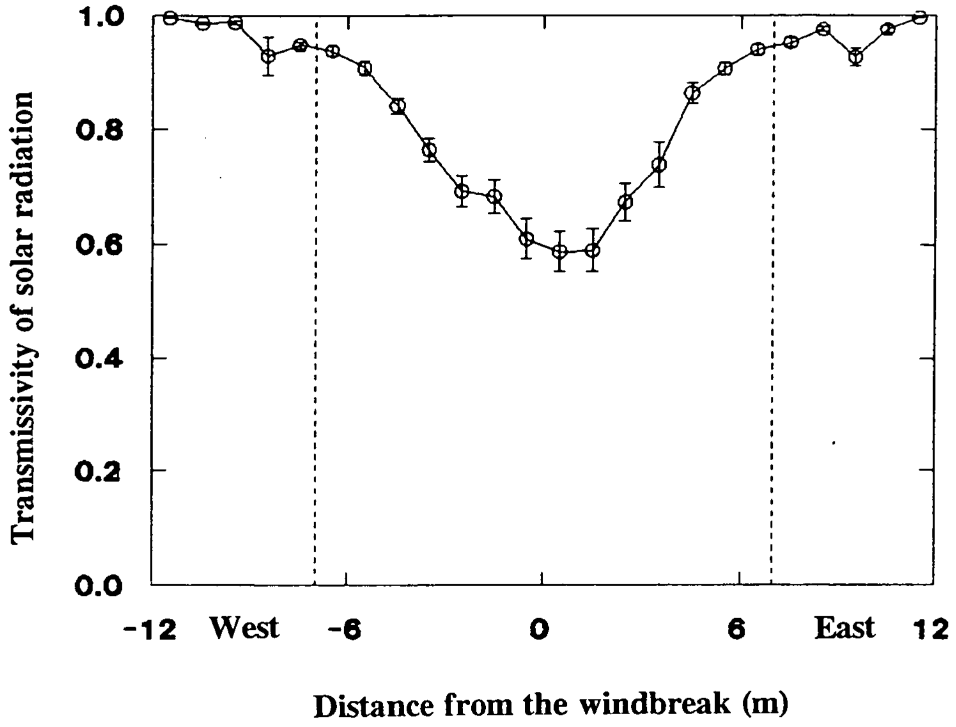


Figure 5.4 Hourly averages of transmitted solar radiation, on eastern and western sides of a windbreak taken at a) 09.00 h, b) 11.00 h, c) 13.00 h, d) 15.00 h, e) 17.00 h. The dotted lines indicate distance of $1h$ on either side of the windbreak, error bars indicate ± 1 s.e.($n = 9$).

Figure 5.5 Average daily transmitted solar radiation on eastern and western sides of a windbreak. The dotted line indicates a distance of 1*h* from the windbreak, error bars indicate ± 1 s.e. (*n* = 9).



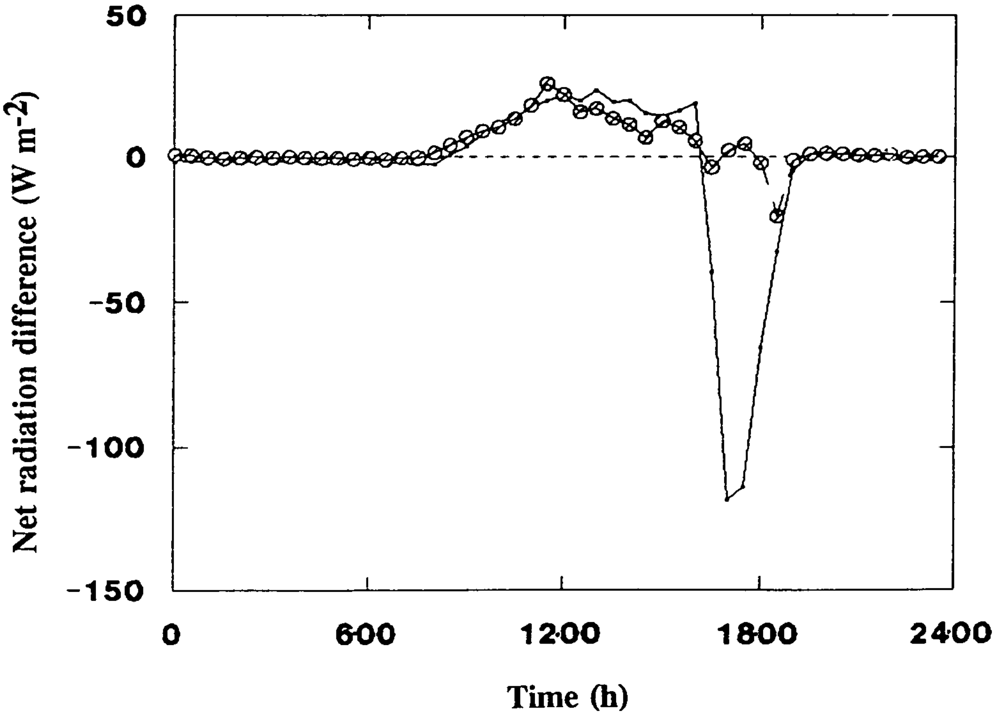


Figure 5.6 Average diurnal pattern of [(R_n at 1*h*) - (R_n at 10*h*)], (average of 37 days) (•), and [(R_n at 3*h*) - (R_n at 10*h*)], (average of 4 days) (o).

5.2.3 Temperature and humidity

5.2.3.1 Air temperature

Air temperature (T_a), vapour pressure (e_a) and vapour pressure deficit (D_a) at crop height depend upon (i) prevailing atmospheric conditions measured at a reference height (temperature (T_o), vapour pressure (e_o) and vapour pressure deficit (D_o)), (ii) net radiation (R_n), (iii) transpiration of the underlying vegetation, and (iv) degree of coupling between the atmosphere and the vegetation. Values of T_o, e_o and D_o were taken at $x = -6h$ and $z = 5$ m, and measurements of T_a, e_a and D_a were taken at $z = 0.7h_c$ (Section 3.2.4 and 3.3.1).

Diurnal patterns of (T_a - T_o) for sunny days during intervals A to D are shown in Figures 5.7a - d. Day-time differences in temperatures were largest towards the middle of the day, ie. maximum R_n, on all days. Highest air temperatures were found at $3h$ on all days, although during interval A, T_a was similar to that at $6h$. Over all other intervals the order of day-time temperatures was $3h > 6h > 10h > 1h$. Table 5.1 gives day-time (08.00 h to 18.00 h) and night-time (19.00 h to 07.00 h) mean and maximum (13.00 h) air temperatures for sunny days during intervals A to D. Values for windward and unsheltered sites are also given, windward air temperatures were not measured at the start of the season.

The lower incident wind speed on the unsheltered as compared to the windward field (Section 4.2.9), resulted in higher temperatures being observed on the unsheltered field than the sheltered field (day 259), and emphasises problems with comparison of micrometeorological data between sites that are 1 km apart, as in the case of the unsheltered control.

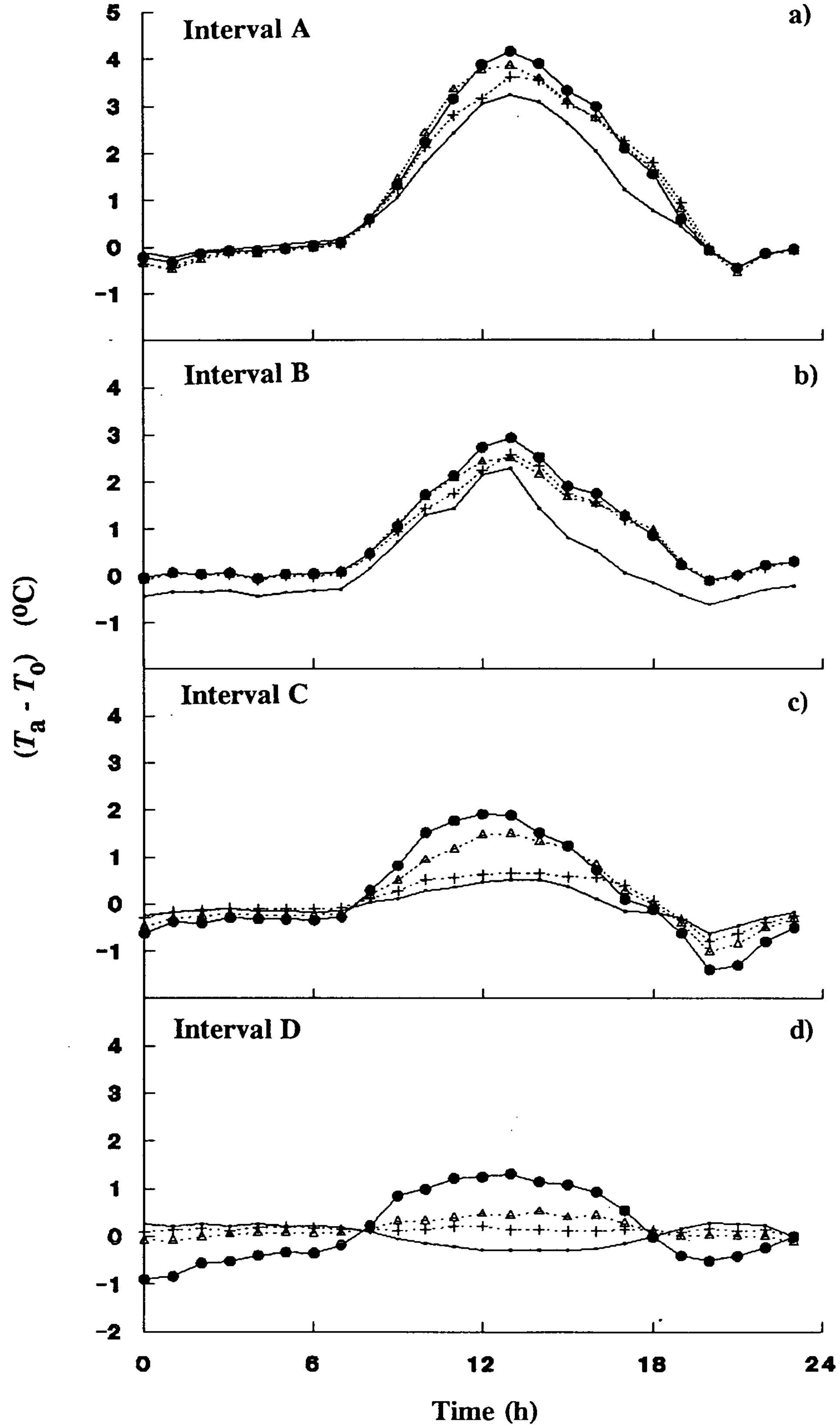


Figure 5.7 Diurnal changes of air temperature difference (T_a - T_o), where T_a was measured at $z = 0.7h_c$ and T_o was measured at z = 5 m, at 1*h* (•), 3*h* (●), 6*h* (△), and 10*h* (+), for a sunny day during a) interval A, b) interval B, c) interval C, d) interval D.

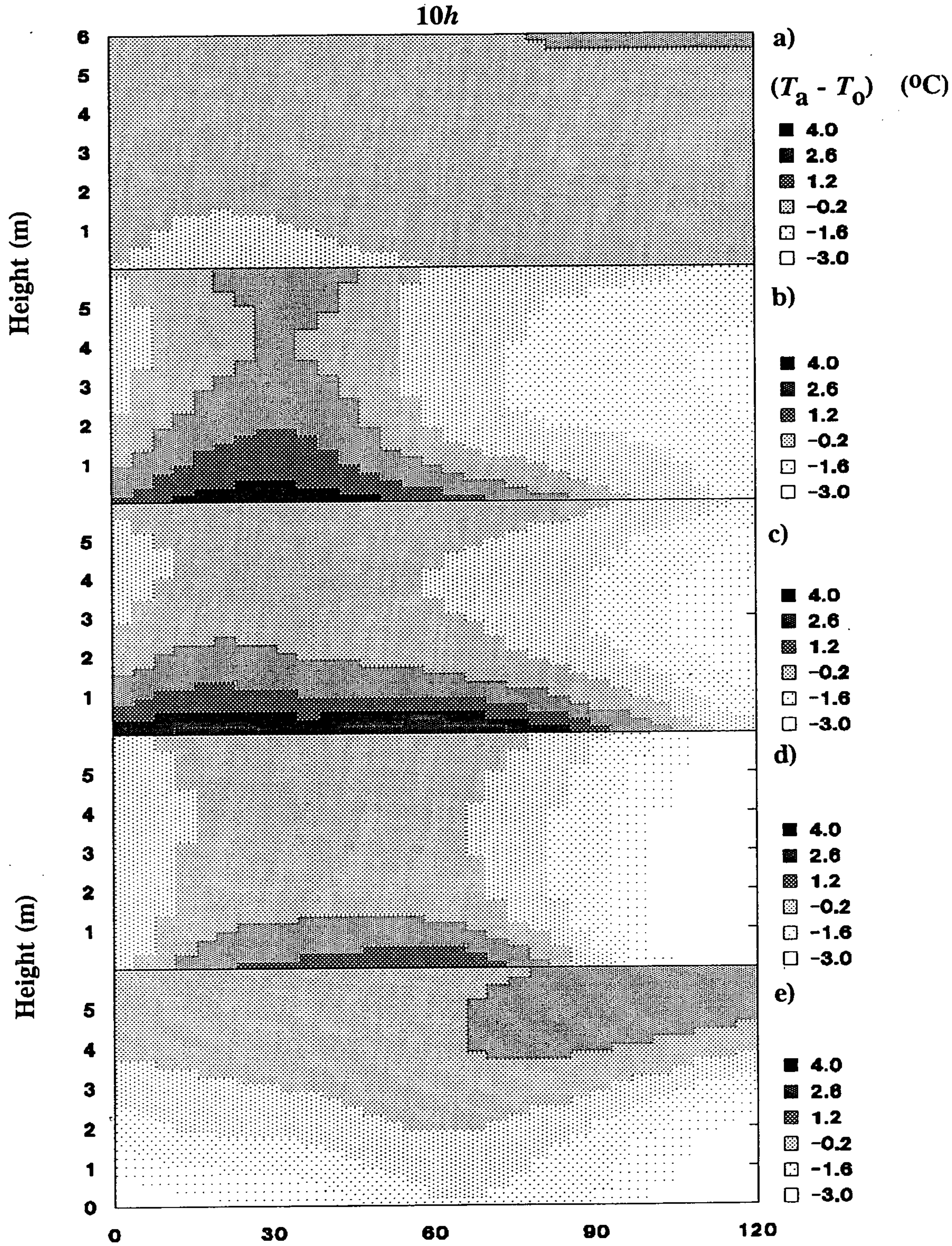
Table 5.1 Air temperatures for sunny days over intervals A to D, measured at $0.7h_c$, values are for specific days.

Day and time	1*h*	3*h*	6*h* °C	10*h*	wind	unsh
201 day *	33.4	34.1	34.1	33.9	-	34.2
201 night *	28.6	28.5	28.5	28.7	-	28.4
201 max *	35.5	36.4	36.1	35.9	-	36.3
225 day	31.5	32.2	32.1	32.0	-	30.5
225 night	26.5	27.0	26.0	27.0	-	27.0
225 max	34.1	34.7	34.3	34.4	-	31.9
248 day	29.0	29.8	29.6	29.2	29.3	30.0
248 night	25.6	25.3	25.5	25.6	25.4	25.9
248 max	30.5	31.9	31.6	30.6	30.9	31.9
259 day	29.7	30.7	30.2	30.0	30.9	33.4
259 night	27.2	26.5	26.9	27.1	27.2	27.1
259 max	31.1	32.6	31.8	31.5	32.4	36.0

wind - windward unsh - unsheltered

* - measured at $z = 0.4$ m (h_c was < 0.4 m)

Figure 5.8 shows the development of (T_a - T_0) over the day, during the latter part of the season (Configuration B), with T_0 taken at $x = -6h$, $z = 5$ m. At night cold air accumulated in the sheltered zone (Figure 5.8a): as R_n became positive the sheltered zone warmed up near the ground becoming the warmest zone by 10.00 h. The warm air zone expanded to 15*h* reaching it's maximum extent at 13.00 h, then decreased in the afternoon as R_n decreased, leading to reestablishment of a zone of cold air at 3*h* by 19.00 h.



Distance from windbreak (m)

Figure 5.8 Air temperature differences (T_a - T_0), behind a windbreak over a day, towards the end of the season. Averaged over 30 minutes at a) 07.00 h, b) 10.00 h, c) 13.00 h, d) 16.00 h, e) 19.00 h. Windbreak height was 6 m.

5.2.3.2 Vapour pressure

The value of (e_a - e_o) was constantly higher at 3*h* than at other distances throughout the season, reaching a maximum over interval C (Figures 5.9a - d). Vapour pressure differences were related to amount of leaf area and wind speed, with largest leaf areas over intervals A and B being at 3*h* and 10*h*, whereas by interval C, *L* was largest at 3*h* which corresponded to a larger e_a. e_a was lower at 1*h* than the rest of the field, with negative values of (e_a - e_o) during interval D. The reasons for this are unclear. The negative (e_a - e_o) values may have resulted from down-drafts of dry air from above 5 m, on the windward side of the windbreak. This air could have been forced under the trees and causing a reduction in e_a at 1*h*. There is also a possibility of instrumental error, but this is unlikely to be as a result of radiation errors, since the radiation incident of all psychrometers was similar over most of the day. Table 5.2 shows vapour pressures measured at 13.00 h on four sunny days over the season.

Table 5.2 Vapour pressure at 13.00 h measured at z = $0.7h_c$, for four individual sunny days over the season.

Distance	Julian Day 201*	225	248	259	(kPa)
1*h*	2.51	2.53	2.61	2.86	
3*h*	2.61	2.70	3.03	3.19	
6*h*	2.53	2.57	2.78	2.97	
10*h*	2.58	2.63	2.78	2.99	
windward			2.82	3.03	

* - measured at z = 0.4 m

Values of e_a on the windward side were lower than at 3*h*, but generally higher than at other points in the sheltered field.

Taking values of e_o from the IH meteorological station (Section 3.2.4), since reliable values of e_o were not available for all days from station 5, the change of

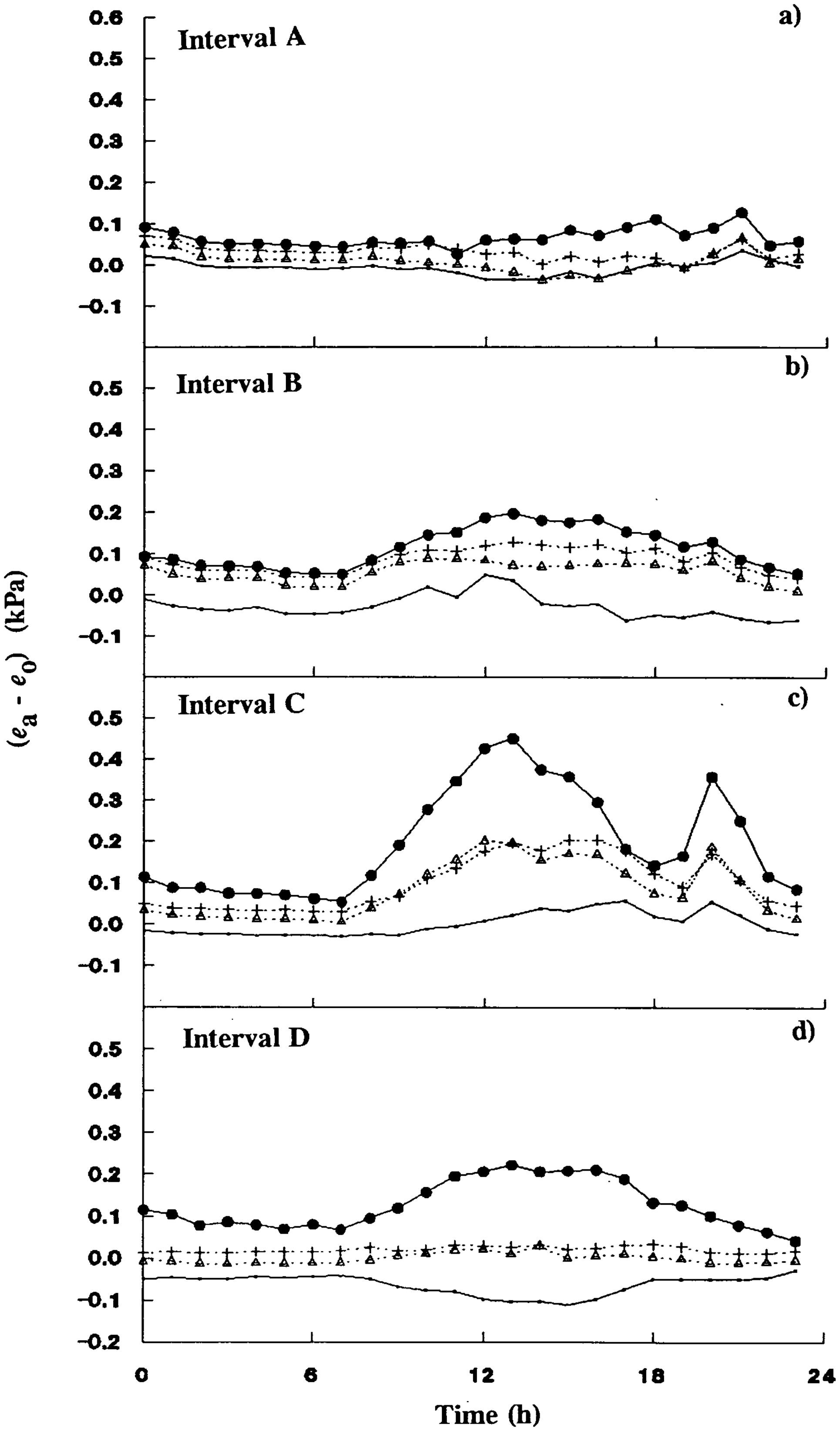
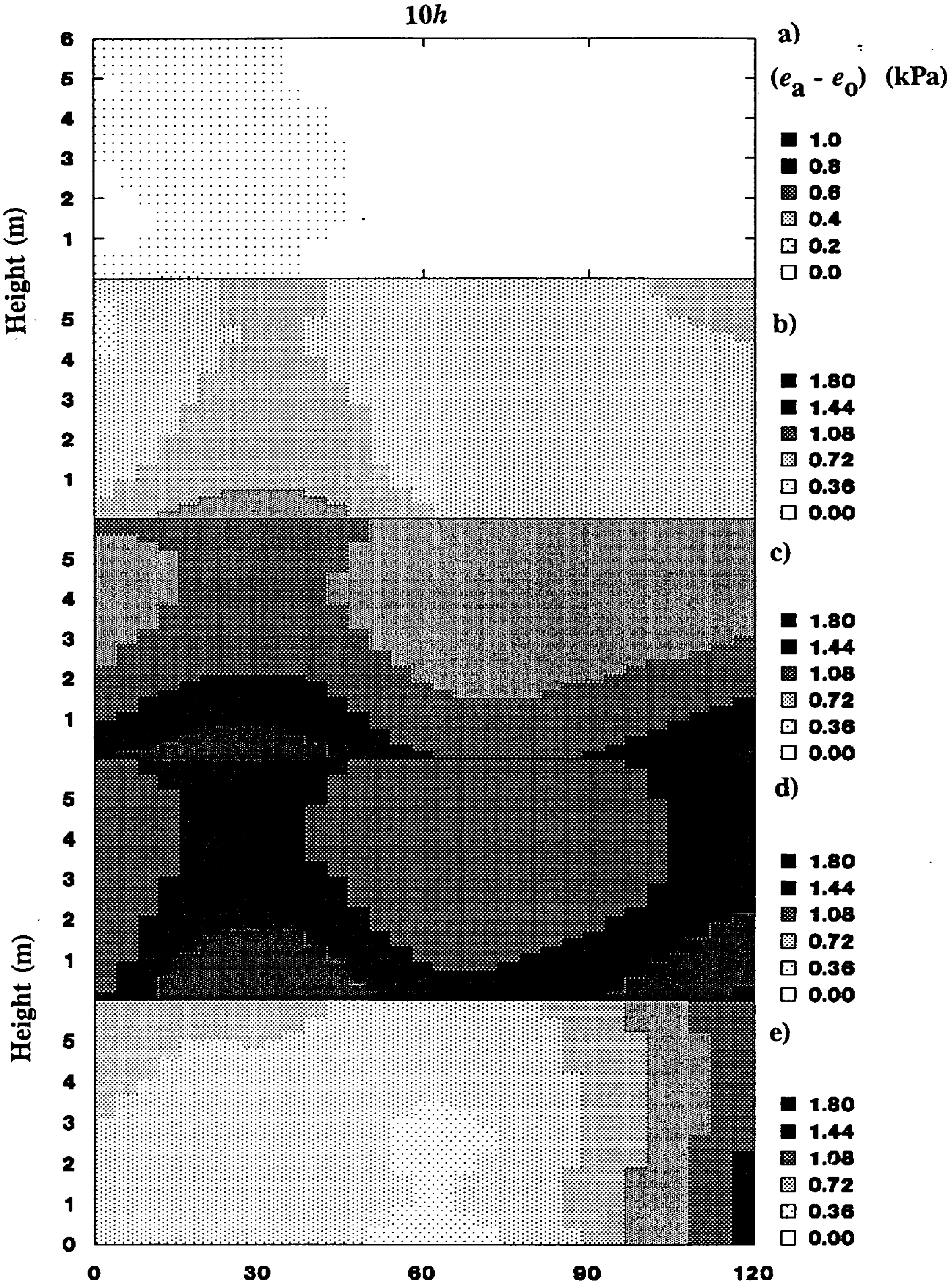


Figure 5.9 Diurnal changes of water vapour pressure difference (e_a - e_0) where e_a was measured at z = 0.7h_c and e_0 was measured at z = 5 m and x = -6h, at 1h (•), 3h (●), 6h (△), and 10h (+), for a sunny day during a) interval A, b) interval B, c) interval C, d) interval D.



Distance from windbreak (m)

Figure 5.10 Water vapour pressure differences (e_a - e_o) behind a windbreak over a day, towards the end of the season. Averaged over 30 minutes at a) 07.00 h, b) 10.00 h, c) 13.00 h, d) 16.00 h, e) 19.00 h.

(e_a - e_o) over a day can be seen (Figure 5.10). The scale on Figure 5.10a is smaller to increase clarity, scales for all other times are the same. Vapour pressure differences increased towards the middle of the day as crop transpiration increased, the highest values occurred at 3*h* corresponding to high ***L*** and low ***u***. A zone of lower vapour pressure appeared to develop between 10*h* and 15*h* corresponding to lower leaf area and higher turbulence (Figure 4.10), indicating a wake zone, (Section 4.3.6). At the beginning and end of the day the gradients of vapour pressure within the field were small.

5.2.3.3 Vapour Pressure Deficit

Vapour pressure deficit, $D_a = e^*_{(Ta)} - e_a$, is dependent on both air temperature and vapour pressure. Increases in T_a and e_a at 3*h* influence D_a in opposite directions. Large differences in e_a (Figures 5.9c and d), are counteracted by increases in T_a, leading to similar D_a across the field, (Figures 5.11c and d). The largest midday (D_a - D_o) at the beginning of the season, resulted from large (T_a - T_o). However, as crop transpiration increased day-time (D_a - D_o) decreased. Table 5.3 gives the changes in D_a over the season.

Table 5.3 Vapour pressure deficit measured at 13.00 h, at $z = 0.7h_c$, on four individual sunny days during intervals A to D.

	Julian day				
Distance	201*	225	248	259	(kPa)
1*h*	3.27	2.82	1.76	1.65	
3*h*	3.47	2.85	1.68	1.75	
6*h*	3.46	2.84	1.83	1.72	
10*h*	3.33	2.81	1.62	1.63	
windward			1.65	1.85	

* - measured at $z = 0.4$ m

The large D_a at the start of the season were caused by high T_a and low e_a, as the season progressed e_a increased and T_a decreased, decreasing D_a during the middle of the season. Towards the end of the season leaf area decreased and the system dried increasing D_a.

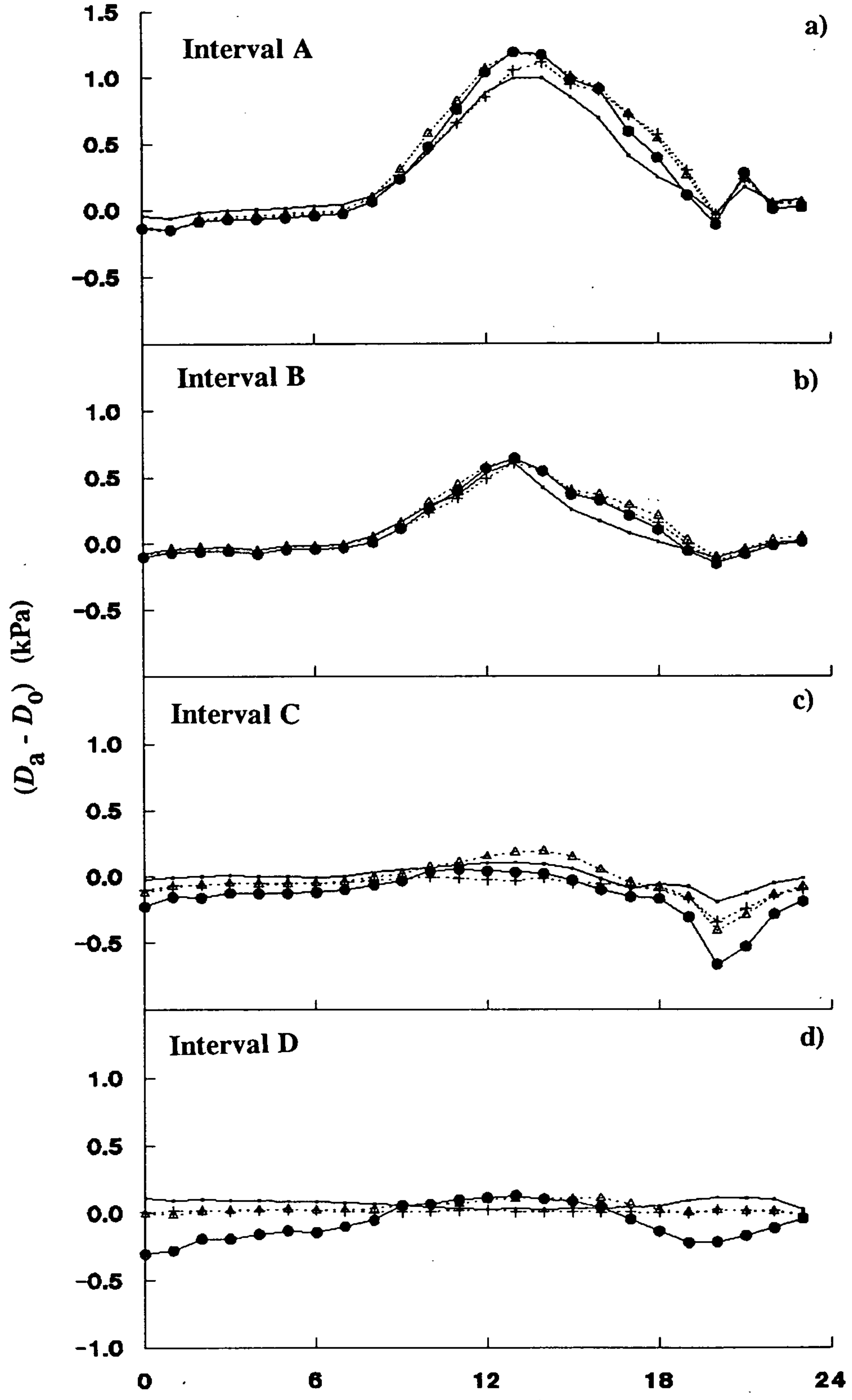


Figure 5.11 Diurnal changes of saturated vapour pressure difference (D_a - D_0), where D_a was measured at z = 0.7h_c and D_0 was measured at z = 5 m and x = -6h, at 1h (•), 3h (●), 6h (△), and 10h (—+—), for a sunny day during a) interval A, b) interval B, c) interval C, d) interval D.

5.2.3.4 Leaf temperature

Leaf temperatures data were selected for days when all leaf thermocouples were known to be attached and the standard deviation of the three pairs of leaf thermocouple did not exceed 1 °C. Table 5.4 presents values of T_l for intervals A to D averaged for four sunny days.

Table 5.4 Mean leaf temperature for intervals A to D, measured in the upper layer of the canopy, day (08.00 h to 18.00 h), night (18.00 h to 08.00 h), ± 1 s.e., (n = 4).

Interval		Day	Night	13.00 h
	Distance		°C	
A	1*h*	33.2 ± 0.9	26.7 ± 0.7	36.7 ± 0.4
	3*h*	34.5 ± 1.1	26.4 ± 0.7	38.1 ± 0.5
	6*h*	34.0 ± 1.0	26.2 ± 0.7	37.5 ± 0.5
	10*h*	33.9 ± 1.0	26.4 ± 0.7	37.4 ± 0.5
B	1*h*	30.7 ± 0.9	24.6 ± 0.6	32.0 ± 1.3
	3*h*	31.0 ± 0.8	24.3 ± 0.7	33.3 ± 1.1
	6*h*	31.4 ± 0.9	24.4 ± 0.6	33.3 ± 1.2
	10*h*	31.2 ± 0.8	24.6 ± 0.6	33.1 ± 1.1
C	1*h*	30.5 ± 0.7	25.7 ± 0.3	32.7 ± 0.8
	3*h*	30.6 ± 0.7	25.1 ± 0.3	32.6 ± 0.7
	6*h*	30.8 ± 0.7	25.3 ± 0.3	32.5 ± 0.9
	10*h*	31.2 ± 0.7	25.6 ± 0.3	33.0 ± 0.8
D	1*h*	29.8 ± 0.3	24.7 ± 0.6	31.4 ± 0.4
	3*h*	30.3 ± 0.7	23.8 ± 0.3	33.2 ± 0.6
	6*h*	29.4 ± 0.6	24.3 ± 0.5	30.9 ± 0.4
	10*h*	30.5 ± 0.7	24.5 ± 0.5	32.6 ± 0.3
E	1*h*	30.8 ± 0.5	24.3 ± 0.5	33.1 ± 0.6
	3*h*	31.6 ± 0.5	23.3 ± 0.5	33.8 ± 0.4
	6*h*	31.6 ± 0.5	23.6 ± 0.5	33.8 ± 0.6
	10*h*	31.9 ± 0.4	24.1 ± 0.5	34.4 ± 0.6

Leaf temperature (T_l) did not show any consistent changes with distance from the windbreak, although day-time and maximum temperatures were generally lower at 1*h*. Average daily T_l decreased from 34 °C to 30 °C, and maximum T_l from 38 °C to 33 °C from interval A to D. One cause of the lack of a consistent trend in T_l maybe the variability of the measurement. If the effect of shelter on T_l was in the order of 2 °C (Section 5.1.3), and the error in measurement was ± 1 °C, (Table 5.4), trends may be obscured by the variability of the measurement.

5.2.3.5 The effect of temperature on millet growth

The effect of an increase in temperature on millet growth depends upon stage of growth, and absolute temperature. Optimum temperatures for growth vary with biological process. Ong and Monteith (1985) reported that germination rates of millet increased linearly with temperature to an optimum temperature Tg_{opt}, above which rates decreased rapidly, Tg_{opt} for millet being 32 to 34 °C. The temperature which the seed experienced is more closely related to soil rather than air temperature. During germination $T_a > Tg_{opt}$, so an increase in temperatures may be detrimental to germination. Growth data at the start of the season (Section 2.4.1) suggested that germination at 6*h* was delayed, however Table 5.1 and Figure 5.7a do not indicate substantially higher T_a at 6*h*. Soil surface temperatures were calculated from the energy balance at midday over interval A, using eq. 5.10 and 5.11;

$$R_n - G_s = 0.8\,(\rho_a\, C_p\, g_a\, (T_s - T_a)) \qquad (5.10)$$

where $R_n - G_s = 339$ W m^{-2} (taken from measurements), and $(T_s - T_a)$ is temperature difference between soil surface and air. It was assumed that $\lambda E = 0.2H$ (Wallace *et al.*, 1989 for dry soil) and that;

$$g_a = ((ku/\ln(z/z_0))^2/\,u) \qquad (5.11)$$

where u is wind speed at $z = 0.4$ m, k is Von Karman's constant (0.41), $z_0 = 0.0065$ m (Section 4.3.2, ridged field), and $z = 0.4$ m (measurement height for T_a). u_0 was taken as 2 m s^{-1}, and u was calculated for each distance from the windbreak using the normalization from Table 4.2. Results from these calculations are shown in Table 5.5.

Table 5.5 Variables calculated to determine soil surface temperatures at 13.00 h for interval A, from eq. 5.10 and 5.11, and measured data.

Variable	1*h*	3*h*	6*h*	10*h*
T_a (°C)	35.5	36.4	36.1	35.9
u (m s^{-1})	1.74	1.48	1.24	1.50
g_a (m s^{-1})	0.0172	0.0146	0.0122	0.0148
$(T_s - T_a)$ (°C)	13.5	15.9	19.0	15.6
T_s (°C)	49.0	52.3	55.1	51.5

These calculations, although approximate, show that substantially larger soil surface temperatures exist in shelter with temperatures exceeding T^g_{opt} and reaching lethal temperatures for millet. High soil surface temperatures (>50 °C) have been recorded by Wallace *et al.* (1989) and ICRISAT (1988). Although absolute values may be slightly overestimated the pattern indicates that reduced growth at 6*h* may have resulted from supra-optimum, approaching lethal, temperatures experienced at the soil surface.

Soil temperatures control growth processes in millet while the meristem is below the soil surface (ODA, 1987a; Corlett, 1989). During this period the maximum number of leaves produced is determined (Ong and Monteith, 1985). The rate of leaf initiation and leaf expansion increase linearly with temperature to an optimum (T^l_{opt}) of around 32 to 34 °C (Ong, 1983a; c). Little is known about leaf temperatures above these temperatures, but data suggest a rapid decline in leaf expansion (Ong and Monteith, 1985). In most cases when $R_n > 0$ W m^{-2} shelter increases leaf temperatures (T_l). An increase in T_l over interval A would be detrimental to leaf growth, however in the subsequent time intervals the increase in leaf temperature may be beneficial to leaf expansion (Terry *et al.*, 1983). The rapid increase in L at 3*h*, may have resulted from the effect of temperature, since the fastest rate of increase of L for millet was found to be at T_a = 31 °C (Squire *et* *al.*, 1984). Temperature affects both the rate of expansion and duration of the canopy (Ong and Monteith, 1985). The advantages of rapid canopy expansion can often be offset by shorter canopy duration, which was noted at 3*h* in both years, (Section 2.4.1). The early senescence of the canopy in 1988 at 3*h* resulted in the unsheltered field (that reached maximum ***L*** two weeks later) yielding more grain and similar biomass by final harvest. The shorter canopy duration in shelter also explains why growth differences are substantially lower by the end, compared to the middle, of the season.

Optimum temperatures for tillering are around 21 ^{o}C (Fussell *et al.*, 1980; Ong and Monteith, 1985). Increased tillering on the control relative to the sheltered field in 1988, may have resulted from lower temperatures, as well as increased stress (Mahalakshmi and Bidinger, 1985).

The optimum temperature for grain yield (T^{s}_{opt}) is lower than T^{l}_{opt}, around 22 to 27 ^{o}C (Ong, 1983b; Fussell *et al.*, 1980), affecting duration rather than rate of grain filling (Fussell *et al.*, 1980; Ong and Monteith, 1985). Sheltered millet had a consistently lower harvest index than unsheltered millet, with many of the measured variables indicating that shelter benefited vegetative growth more than reproductive growth, ie. smaller grains, lighter panicles, etc. (Section 2.4.2).

So some of the effects of shelter on millet growth can be explained by the effects of shelter on temperature and consequently on millet growth. Reductions in growth in shelter at the start of the season resulted from lethal soil temperatures affecting germination and early growth. Water stress at the start of the season could also have delayed plants at 6*h*. As the season progressed higher air and leaf temperatures in sheltered zones produced faster expanding canopies increasing light interception, however reducing the duration of the canopy. Higher air temperatures in shelter encouraged early panicle emergence but shortened the duration of grain filling. Early maturity meant that final harvest grain yield was not substantially improved in shelter although vegetative production was, reducing the harvest index.

5.2.4 Conversion coefficient

The growth of a plant depends on the efficiency that light is converted to dry matter as well as the amount of radiation intercepted. The relationship between solar radiation intercepted and dry matter accumulation is linear for millet over the vegetative growth part of the season (Monteith, 1972; ODA, 1987a). Intercepted solar radiation (S_i) was calculated from equation 5.12;

$$S_i = S_t(1 - t_s) \tag{5.12}$$

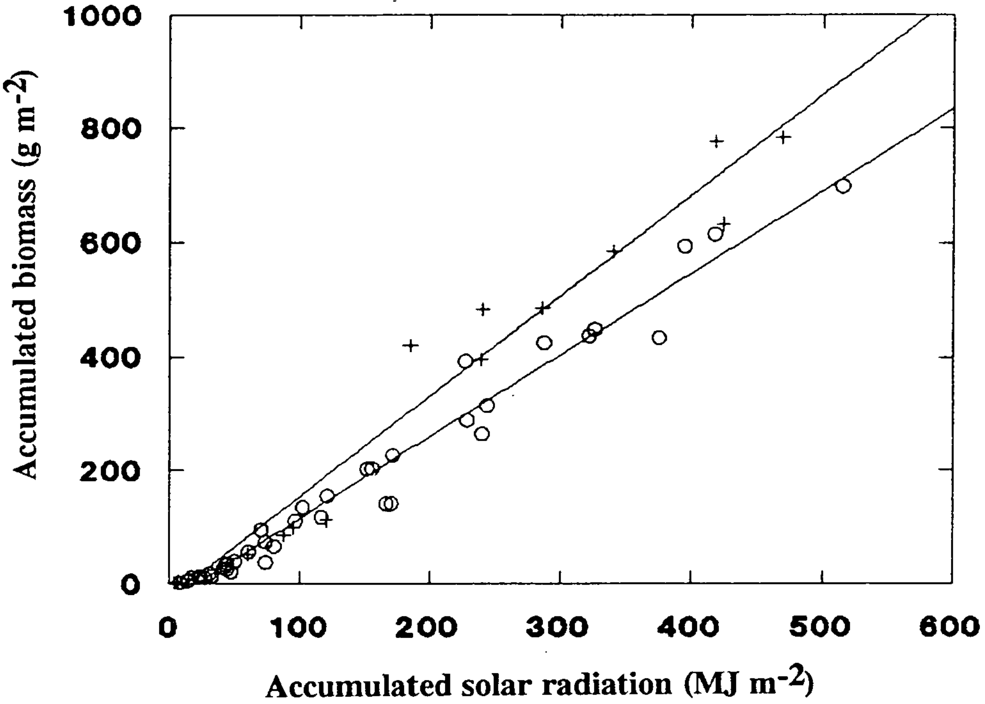
where t_s is the transmissivity to solar radiation;

$$t_s = e^{-KL} \tag{5.13}$$

where L was calculated from Section 2.4.1, and K is the extinction coefficient for solar radiation, taken as 0.43 (Wallace *et al.*, 1989). Daily values of S_t and L were used to calculate S_i. The slope of the line of Figure 5.12 is the conversion coefficient ($\hat{e}$) and was 1.76 g MJ^{-1} in 1988 and 1.44 g MJ^{-1} in 1989, averaged for all distances from the windbreak. These data compare well with values found by ODA (1987a) of 1.2 g MJ^{-1} for Niamey in the dry season and 1.7 g MJ^{-1} for Hyderabad (India) in the dry season. Values of $\hat{e}$ increased as atmospheric humidity increased: 1988 was a wetter year than 1989 and Hyderabad in the rainy season had $\hat{e} > 2.0$ g MJ^{-1} reaching as high as 2.5 g MJ^{-1} in a glasshouse in Sutton Bonnington, U.K.. Charles-Edwards (1982) calculated an upper limit to $\hat{e}$ of around 3.2 g MJ^{-1} (assuming eq. 5.1), and quoted values for a range of crops of between 0.65 to 2.1 g MJ^{-1}.

The changes of $\hat{e}$ over the season were calculated between harvests for time intervals A to D, for distances 1*h* to 20*h* and the unsheltered field, (Figure 5.13). At the start of the season $\hat{e}$ was small as were the differences between different positions. By interval C, the largest $\hat{e}$ was at 3*h*, but this decreased by interval D. At distances exceeding 3*h*, $\hat{e}$ continued increasing to interval D. As millet becomes reproductive $\hat{e}$ decreases to < 1.0 (ODA, 1987a; Corlett, 1989; Begue *et al.*, 1991) so the decrease in $\hat{e}$ of the millet at 3*h* to interval D suggested that it had moved into its reproductive phase before the millet

Figure 5.12 Accumulated intercepted solar radiation and accumulated biomass for millet in 1988 (+) and 1989 (o), for all distances from the windbreak, and all sequential harvests.



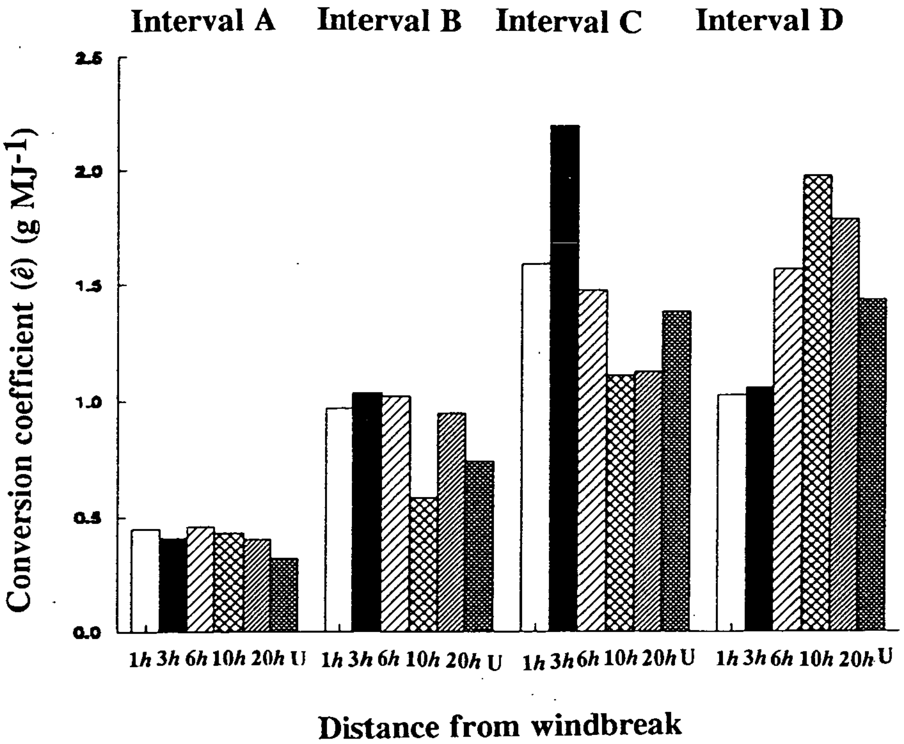


Figure 5.13 Solar radiation conversion coefficient for intervals A, B, C and D, at five distances from the windbreak and the unsheltered field (U).

at the other distances. Although the values of $\hat{e}$ seem high they are similar to the results found for millet by many workers (ODA, 1987a; Begue *et al.*, 1991; Fechter, unpublished data). It is possible by using the intercepted value for solar radiation rather than measuring the absorbed solar radiation values, $\hat{e}$ may be overestimated by around 8 % (Begue *et al.*, 1991).

5.2.5 Stomatal conductance

Stomatal conductances were calculated as adaxial + abaxial conductances (Körner *et al.*, 1971) in cm s^{-1}, average values are also given in mmol m^{-2} s^{-1}, using measured values of leaf temperature.

2.2.5.1 1988 conductances

Differences in g_s with distance from the windbreak for sampling days in 1988 are summarised in Table 5.6. Higher g_s was found in the middle of the canopy (Figure 5.14), with differences between leaves decreasing towards dusk. This agrees with conductances found for sparse millet (Wallace *et al.*, 1990; Azam-Ali, 1983), although denser millet tends to have higher conductances at the top of the canopy (Henson *et al.*, 1982; Squire, 1979).

The ratio of abaxial g_s: adaxial g_s averaged 2.34, higher than that found by Wallace *et al.* (1990). The ratio did not vary significantly with position or treatment, with higher ratios at the start of the day, that may be explained by the different stomatal responses on the abaxial and adaxial surfaces (Henson *et al.*, 1982).

Stomatal conductances at 3*h* were significantly higher on days II and III (Figures 5.15b - c) with differences decreasing towards the end of the day. The midday value of g_s on day I, 3*h* (Figure 5.15a) was the only case of a significant reversal of this trend, whereas on day IV (Figure 5.15d) there were no significant differences after 11.00 h. Daily mean conductances on days II and III were 1.56 cm s^{-1} (624 mmol m^{-2} s^{-1}) and 1.44 cm s^{-1} (576 mmol m^{-2} s^{-1}), respectively, higher than those on day I and IV of 1.08 cm s^{-1} (432 mmol m^{-2} s^{-1}) and 1.06 cm s^{-1} (424 mmol m^{-2} s^{-1}), respectively.

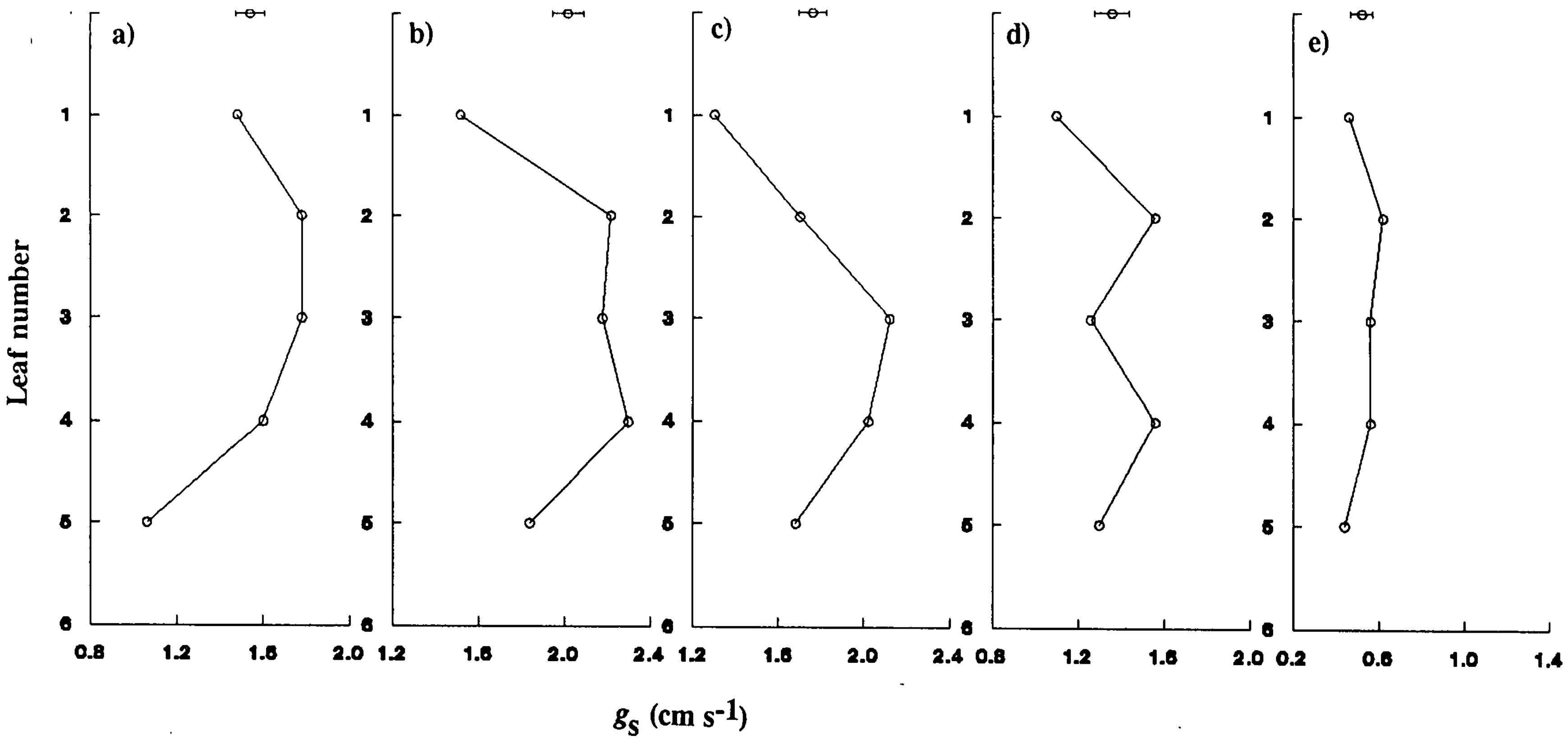


Figure 5.14 Changes of stomatal conductance (g_s) within a millet crop with leaf number, over the course of a day for day III, 1988. Error bars indicate ± 1 pooled s.e. (n = 4). Measurements were taken at a) 09.00 h, b) 11.00 h, c) 13.00 h, d) 15.00 h, e) 17.00 h.

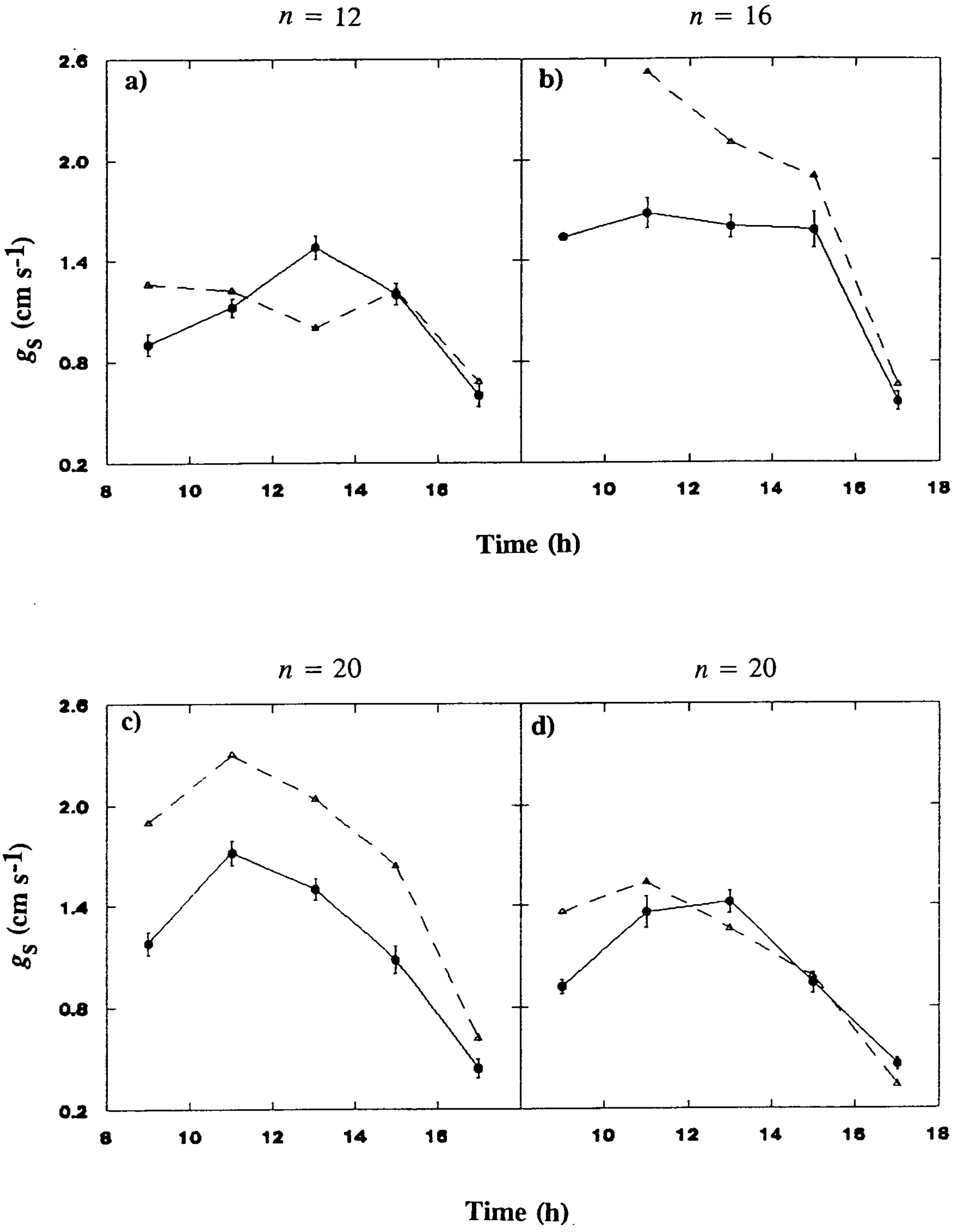


Figure 5.15 Diurnal patterns of stomatal conductance (g_S) averaged for alternate leaves, and four plants, for 1*h* (●), and 3*h* (△), for a) day I, b) day II, c) day III, d) day IV. Error bar indicate ± 1 pooled s.e..

Table 5.6 Millet stomatal conductances 1988 (cm s^{-1}), averaged for four plants and alternate leaves.

Time	Day I		Day II		Day III		Day IV	
	$n = 12$		$n = 16$		$n = 20$		$n = 20$	
(h)	$1h$	$3h$	$1h$	$3h$	$1h$	$3h$	$1h$	$3h$
09.00	0.90	1.26 ***	1.54	nt	1.18	1.90 ***	0.92	1.36 ***
11.00	1.12	1.22 ns	1.68	2.52 ***	1.72	2.30 ***	1.36	1.54 ns
13.00	1.48	1.00 ***	1.60	2.10 ***	1.50	2.04 ***	1.42	1.26 ns
15.00	1.20	1.22 ns	1.58	1.90 ns	1.08	1.64 ***	1.54	0.98 ns
17.00	0.60	0.64 ns	0.56	0.66 ns	0.44	0.62 ns	0.46	0.34 ns
mean	1.06	1.08 ns	1.36	1.80 ***	1.18	1.70 ***	1.02	1.10 ns

nt - not taken   ns - not significant   *** - significant at 0.1%

5.2.5.2 1989 conductances

Measurements in 1989 covered the whole field from $1h$ to $20h$. The average g_s ratio abaxial : adaxial was 1.79, lower than 1988. This may have resulted from measuring later in the day, since the ratio decreases at high quantum fluxes (Henson *et al.*, 1982).

Analysis of variance of g_s showed no significant interaction between depth in the canopy and distance from windbreak, and no significant changes in g_s between layers on days I and III, although conductances were significantly higher on day II in upper and middle layers.

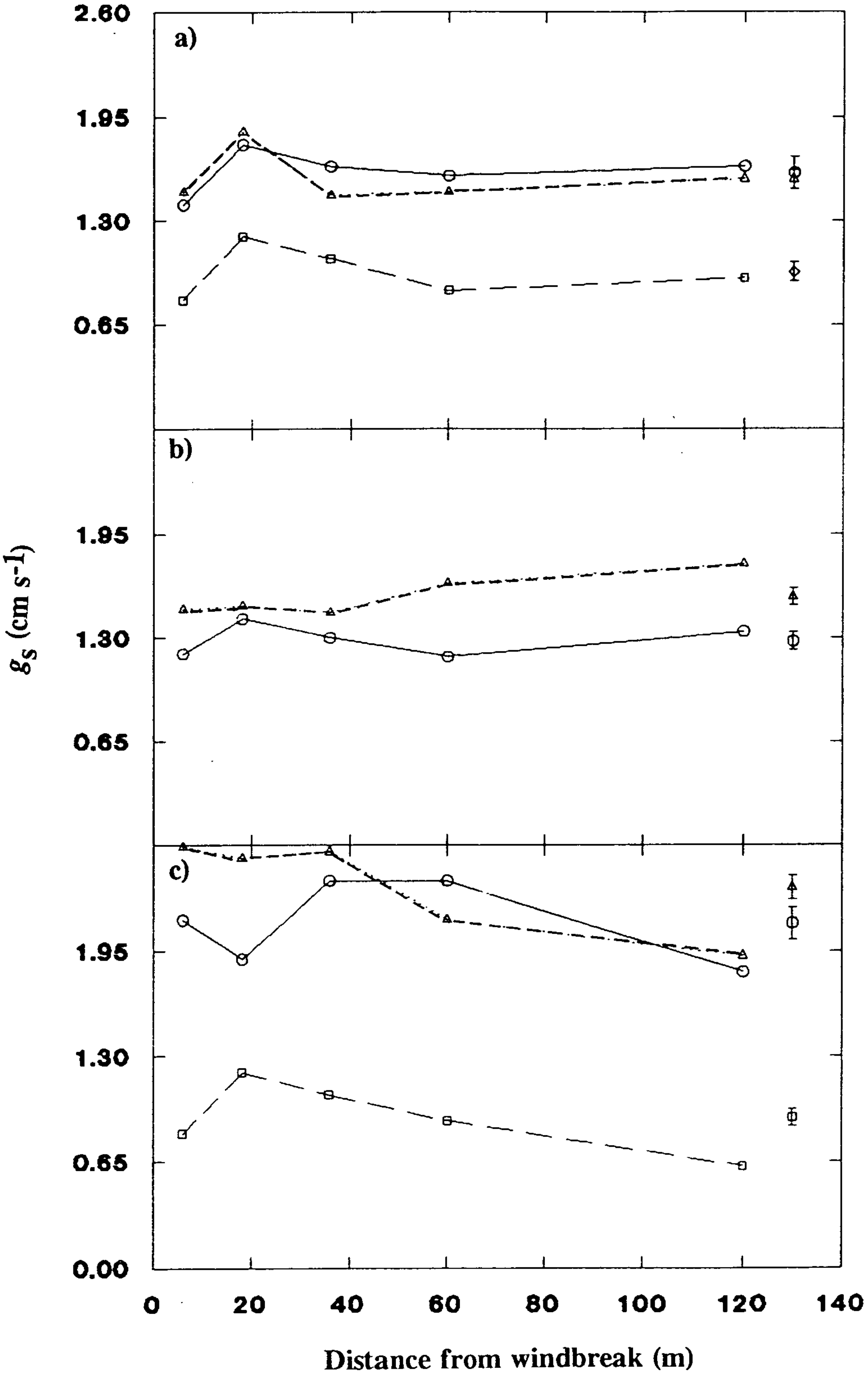


Figure 5.16 Changes of stomatal conductance (g_S) with distance from the windbreak, at 10.00 h (o), 13.00 h (△), 16.00 h (□), on a) day I, b) day II, c) day III. Error bars are ± 1 pooled s.e., (n = 9).

Day I had maximum g_s at 3*h* throughout the day (Figure 5.16a). None of the individual times showed a significant effect of distance on g_s, but analysis over a day gave significant differences in g_s with distance at the 5 % level. There was no significant effect of distance on g_s on day II (Figure 5.16b), although measurements at 10.00 h indicated a similar pattern to that seen on day I. Significant differences in g_s over day III (Table 5.7) with distance from the windbreak (Figure 5.16c), resulted from lower values at 20*h*. Average values of g_s over the three days were 1.38, 1.44 and 1.80 cm s^{-1} (544, 561, 710 mmol m^{-2} s^{-1}) similar to g_s in 1988. Table 5.7 contains a summary of the results.

Table 5.7 Mean daily stomatal conductance 1989 (cm s^{-1}), averaged for three layers in the canopy, three plants, and three sampling times (10.00 h, 13.00 h, and 16.00 h), (n = 27).

Distance	Day I	Day II	Day III
1*h*	1.21	1.34	1.86
3*h*	1.62	1.46	1.88
6h	1.38	1.38	2.00
10*h*	1.30	1.42	1.80
20*h*	1.38	1.56	1.46
	*	ns	**

* significant at 5 %   ** significant at 1 %

The stomatal conductances measured over the two years ranged between 1.0 to 2.0 cm s^{-1} and are relatively high, although not abnormal, for well-watered millet. Körner *et al.* (1971), described cultivated C4 grasses as the group of plants with the highest stomatal conductance. Maximum conductances in millet in Niger of 1.2 cm s^{-1} (Wallace *et al.*, 1990), and between 1.0 and 2.0 cm s^{-1} (Azam-Ali, 1983) have been recorded, although conductances as high as 3 cm s^{-1} were measured at Sutton Bonnington (Black and Squire, 1979).

Henson *et al.* (1982) suggested that after flowering millet stomata open to maximize photosynthesis rather than to minimize water loss. Such a change of stomatal action after flowering in millet has also been found in Niger (Roberts, personal communication). High stomatal conductance also reduces leaf temperatures, which may be beneficial in terms of canopy duration (Section 5.2.3.5).

5.2.5.3 Response of stomatal conductance to light and humidity

Using a combination of eqs. 5.4a and b and eq. 5.5, a model was fitted by a least squares procedure to values of g_s, for measured values of Q and D_a, for days I and III 1989, (day II was not included since it rained in the afternoon) of the type;

$$\text{if } Q < Q_{sat} \qquad g_s = g_{smax} - b_q(Q_{sat} - Q) - b_d(D_a) \qquad (5.14a)$$

$$\text{if } Q => Q_{sat} \qquad g_s = g_{smax} - b_d(D_a) \qquad (5.14b)$$

The goodness of fit of the model was improved significantly by the inclusion of D_a for both days. Individual models for each day fitted significantly better than a combined model for both days (see Section 2.3 for method). Parameters for the models are given in Table 5.8.

Table 5.8 Parameters of stomatal response model (5.14a and b) for days I and III, calculated using a least square procedure. $n = 135$.

Variable	Day I	Day III
g_{smax} (cm s^{-1})	2.139	2.820
Q_{sat} (μmol m^{-2} s^{-1})	1058	720
b_q (cm^3 μmol^{-1})	0.0012	0.0025
b_d (cm s^{-1} kPa^{-1})	0.178	0.309

Turner (1991) showed a linear decline of g_s with increasing leaf to air vapour pressures for nine tree and crop species. Millet g_s declined linearly from 3.0 to 0.5 cm s^{-1} as D_a increased from 1.5 kPa to 2.7 kPa, (Black and Squire, 1979). At high light levels b_d = 0.11, but decreased with decreasing S_t, b_d also decreased with increasing drought stress (Black and Squire, 1979). A decrease in b_d with drought stress would be expected if stomatal conductance was controlled by soil water potentials rather than D_{surf} at low soil water potentials (Szeicz *et al.*, 1973; Davies and Zhang, 1991).

5.2.5.4 Vapour pressure deficit at surface of leaf

Stomata respond to the vapour pressure deficit at the leaf surface (D_{surf}) rather than D_a, (Aphalo and Jarvis, 1991; Bakker, 1991; Grantz and Meinzer, 1991). D_{surf} was calculated using equation 5.6., with values of e_a (Table 5.2) measured at $0.7h_c$, T_l (Table 5.4) and g_s measured in the upper layer of the canopy (gradients within the canopy were not large, Figures 3.6, 5.14). Values were taken at 13.00 h on days from intervals A to D, g_a was calculated for an incident wind speed of 1 m s^{-1}, using equation IV.12 and normalized wind speeds from Table 4.2.

Table 5.9 Values of D_{surf} (kPa) at 13.00 h for time intervals A to D, calculated using eq 5.6, and measured micrometeorological data.

Distance	Interval	A	B	C	D
1*h*		3.27	1.73	1.80	1.11
3*h*		3.59	1.72	1.28	1.14
6*h*		3.44	1.93	1.57	0.94
10*h*		3.40	1.86	1.68	1.30

The values calculated here are for leaves in the upper layer of the canopy, corresponding to approximately $0.7h_c$, the theoretical surface of the crop. Differences in D_{surf} with distance from the windbreak became larger towards the middle of the season when leaf size, e_a and transpiration rates were larger.

The largest differences between g_s at 3*h* and g_s in the rest of the field occurred in the middle of the season in both 1988 and 1989. Whereas at the end of the season, ie. after flowering, differences in g_s with distance fom the windbreak were small in both years. At the beginning of the season (day I, 1988) g_s at 13.00 h at 3*h* was lower than g_s at 1*h*, this can now be explained by the expected increase in D_{surf} at 3*h*, since differences in e_{surf} with distance from the windbreak were small, and temperatures were higher in shelter. This may also explain why under irrigated conditions stomatal conductance increased in shelter, whereas under dryland conditions it decreased (Frank and Willis, 1972; Radke and Hagstrom, 1973; Frank *et al.*, 1974; Carr, 1985).

5.2.5.5 Relationship between vapour pressure deficit at the surface of the leaf and conversion ratio

Comparison of D_{surf} (Table 5.9) and $\hat{e}$ (Figure 5.13) for intervals B and C when the millet was in its vegetative growth stage, (Figure 5.17), shows a good (r^2 = 0.66, n = 8) negative correlation between the variables. The equation was $\hat{e} = -1.99\,D_{surf} + 4.630$. Squire *et al.* (1986) reported a decrease in $\hat{e}$ of 20 % when D_a increased by 1 kPa, and ODA (1987a) concluded that changes in $\hat{e}$ with D_a were accounted for by changes in g_s. Garcia *et al.* (1988) reported changes in $\hat{e}$ for wheat with growth stage and suggested that it was temperature dependent caused by a change in respiration rate and mesophyll conductance.

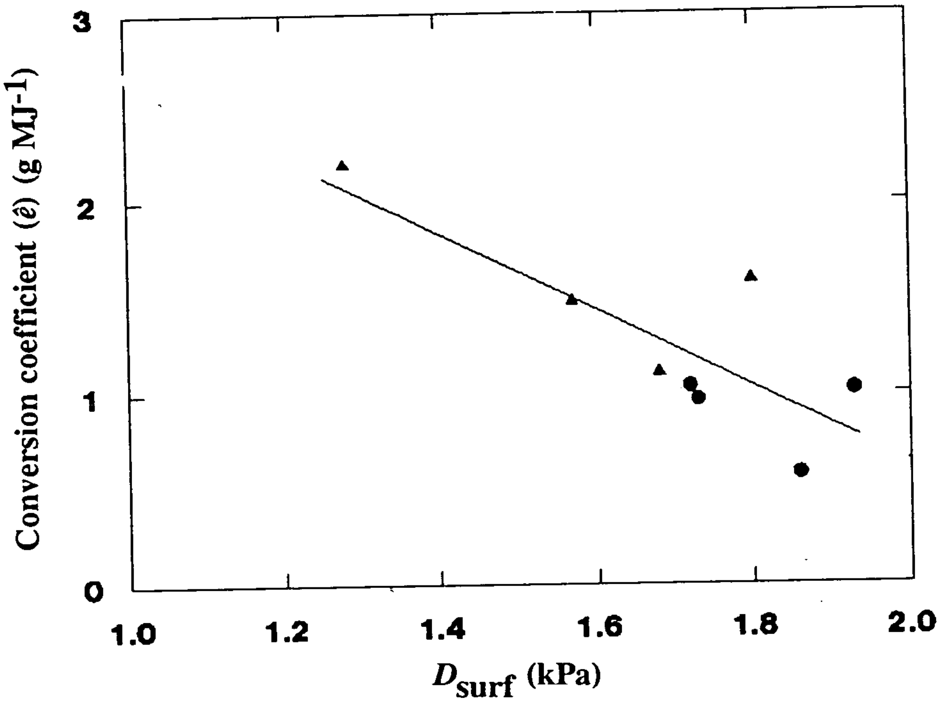


Figure 5.17 Change of solar radiation conversion coefficient with midday values of vapour pressure deficit at the surface of the leaf (D_{surf}), for intervals B (●), and interval C (▲), (r^2 = 0.66, n = 8).

Although the effects of temperature and growth stage cannot be separated using this data-set from the effects of D_{surf}, there seems to be an effect of shelter in increasing g_s resulting from a decrease in D_{surf} leading to an increases *ê*.

The change of D_{surf} with shelter depends on the amount of change in temperature and vapour pressure. In general shelter increases both humidity and temperature, so in a wet system where transpiration or evaporation is high, the increase in humidity exceeds the increase in temperature reducing D_{surf} and causing an increase in g_s, which at high light levels increases the intercellular CO_2 concentration, increasing the efficiency of carbon fixation, which is seen as increased *ê*.

However, if the system is dry, transpiration from the vegetation is low, the temperature increase in shelter may exceed the humidity increase, increasing D_{surf} decreasing g_s, and increasing the resistance of the CO_2 pathway resulting in reduced *ê*.

5.2.6 Transpiration and evaporation

5.2.6.1 Transpiration equations

Transpiration was calculated using equation 5.15 (Jones, 1983);

$$E = 0.622\, g_{leaf}\, \rho a\, (e_l - e_a) \,/\, P \qquad (5.15)$$

where E is transpiration from the leaf (g m^{-2} s^{-1}), 0.622 is the ratio of the molecular weights of water : air, P is atmospheric pressure and $e_l = e^*_{(Tl)}$. Transpiration was calculated for three layers, using measured values of g_s. g_a was calculated from equations IV.12 and was multiplied by 0.84 and 0.75 for the middle and lower layers of the canopy, respectively, after 50 DAS when $L > 0.5$ (Table 4.6). L for upper : middle : lower layers was divided in the proportions 0.33 : 0.33 : 0.33 up to 50 DAS, after which it was divided, 0.4 : 0.5 : 0.1 (Wallace *et al.*, 1989): L was taken from Section 2.4.1. e_a was assumed to be the same for each layer, however T_l was adjusted for the middle and lower layers by measured differences given in Section 3.3.1.2, which varied with time of day. Transpiration was calculated for each layer using measured values of e_a, T_l and u, and weighted by the proportion of the canopy in that layer to give average canopy transpiration on a leaf area basis, which was multiplied by L to give total transpiration for the canopy.

Penman-Monteith transpiration for a leaf in each canopy layer was calculated using equation 5.16;

$$\lambda E = (sR_n^a + \rho a\, Cp\, D_a\, g_a^h) / (s + \gamma (g_a^h / g_{leaf})) \qquad (5.16)$$

where s is the slope of the saturated vapour pressure against temperature curve, and R_n^a is net radiation absorbed by a leaf in the layer, which was calculated using equation 5.17;

$$R_n^a = (R_n (1 - e^{-KL})) / L \qquad (5.17)$$

taking extinction coefficient (K) for net radiation in a millet crop as 0.41 (Wallace *et al.*, 1989). R_n^a for the middle and lower layers was calculated as R_n absorbed by the canopy to the bottom of the layer being calculated, minus R_n^a of the layers above. Penman evaporation was calculated by substituting g_a^v for g_{leaf} in eq. 5.16 and air temperature was used to calculate s.

5.2.6.2 Comparison of transpiration equations

The same input variables and leaf area index weightings were used for comparison of results from eqs. 5.15 and 5.16. Transpiration values calculated from eq. 5.15 and 5.16 for 6*h* on a day during intervals A, B and D, showed underestimation of transpiration by the Penman-Monteith equation (PM) when compared to eq. 5.15. (Figure 5.18). The difference between the two calculations decreased from interval A to D and was largest at the middle of the day. Similar differences in transpiration were predicted by Wallace *et al.* (1990), when comparing the Shuttleworth and Wallace (1985) sparse crop model against the PM equation for a millet crop with low leaf area. The difference between the two models is the inclusion of an energy balance calculation for the soil, so that the effect of heat or vapour fluxes from the soil are taken into account. Ignoring the flux of heat from the soil caused a major underestimation of canopy temperature and resulted in an underestimation of transpiration. As leaf area increased the importance of fluxes from the soil decreased (Figure 5.18). Errors in calculation of R_n^a using equation 5.17 may have resulted from errors in assumptions of extinction coefficient and uniformly distributed foliage. Differences between PM predicted transpiration and that calculated from eq 5.15 averaged over four days for each time interval are

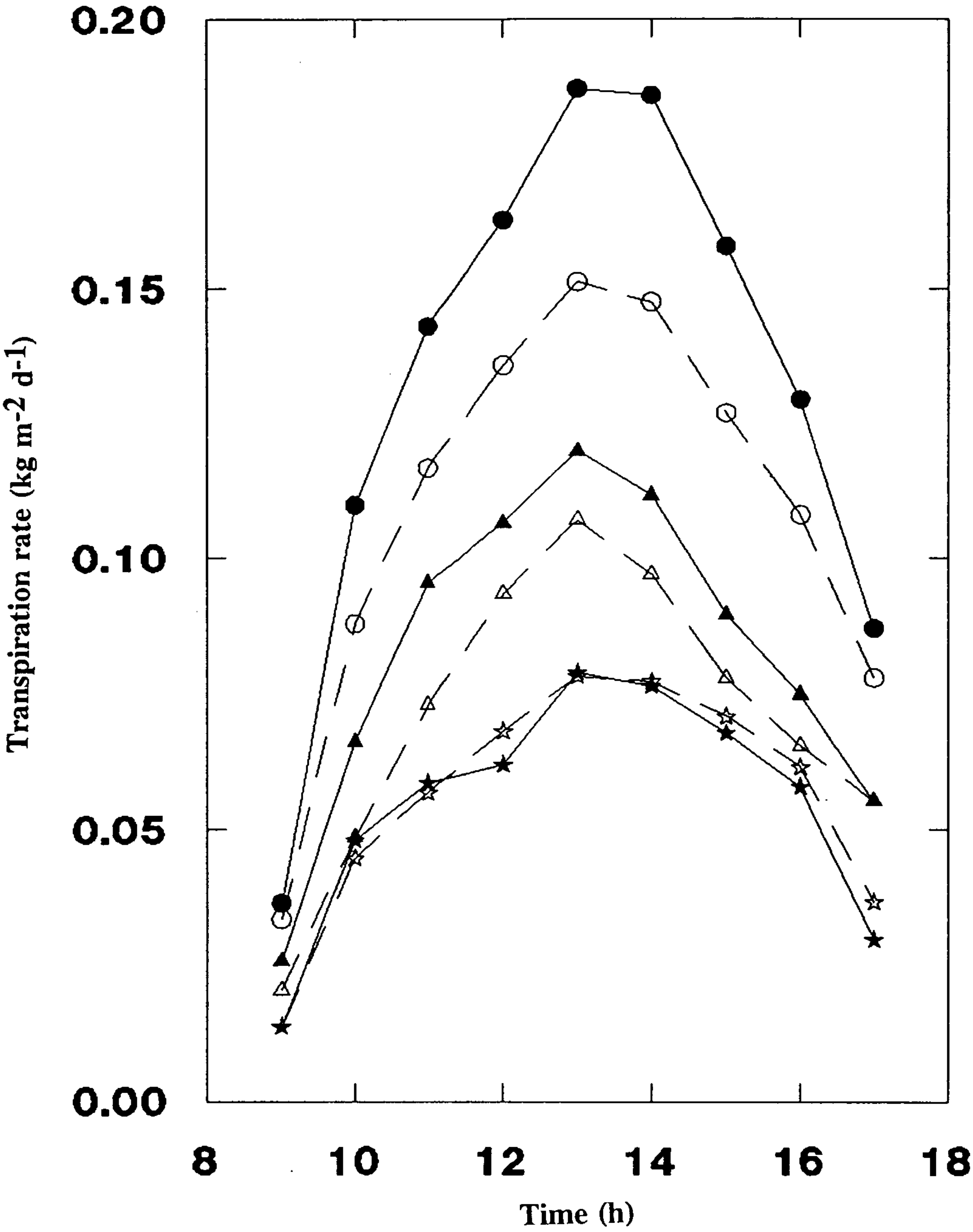


Figure 5.18 Diurnal transpiration rates of millet at a distance of 6*h* behind a windbreak, calculated using eq. 5.15 (closed symbols) and the Penman-Monteith equation, (open symbols). For interval A (day 201 ●), interval B (day 229 ▲), and interval D (day 259 ★).

presented in Table 5.10.

Table 5.10 Differences in daily mean transpiration per unit leaf area predicted from the PM equation and eq. 5.15., for all distances from the windbreak, over four time intervals during the season (n = 16).

Interval	Average Transpiration	eq 5.15 - PM ± s.e. (kg m^{-2} d^{-1})	% difference	L
A	4.07	0.64 ± 0.010	15.7	0.06
B	2.39	0.32 ± 0.005	13.4	0.21
C	2.22	0.18 ± 0.005	8.1	1.1
D	1.90	0.01 ± 0.004	0.005	2.0

An error could be introduced into the PM equation by the use of s at air rather than the average of air and leaf temperature (McArthur, 1990). Using data from Tables 5.1 and 5.4 the maximum difference between T_a and $(T_l + T_a)/2$ was 0.7 K and was not likely to introduce a significant error in to the estimation of λE.

5.2.6.3 Change of transpiration and evaporation with distance from windbreak

Changes of transpiration calculated from the PM equation, eq. 5.15 and evaporation were calculated at four distances from the windbreak (Figure 5.19). The error bars on the evaporation plot represent the s.e. of the day to day variability over the four measurement days. The error bars on the histogram represent the s.e. of the difference between $3h$ and the other distances from the windbreak and the error bars on the PM data respresent s.e. of the difference between the two methods of calculating transpiration. Transpiration per unit leaf area was high (4 kg m^{-2} d^{-1}) at the start of the season resulting from the high evaporative demand, decreasing to around 2 kg m^{-2} d^{-1} by the middle of the season.

The patterns of transpiration and evaporation are markedly different, decreases in evaporation were mirrored by increases in transpiration.

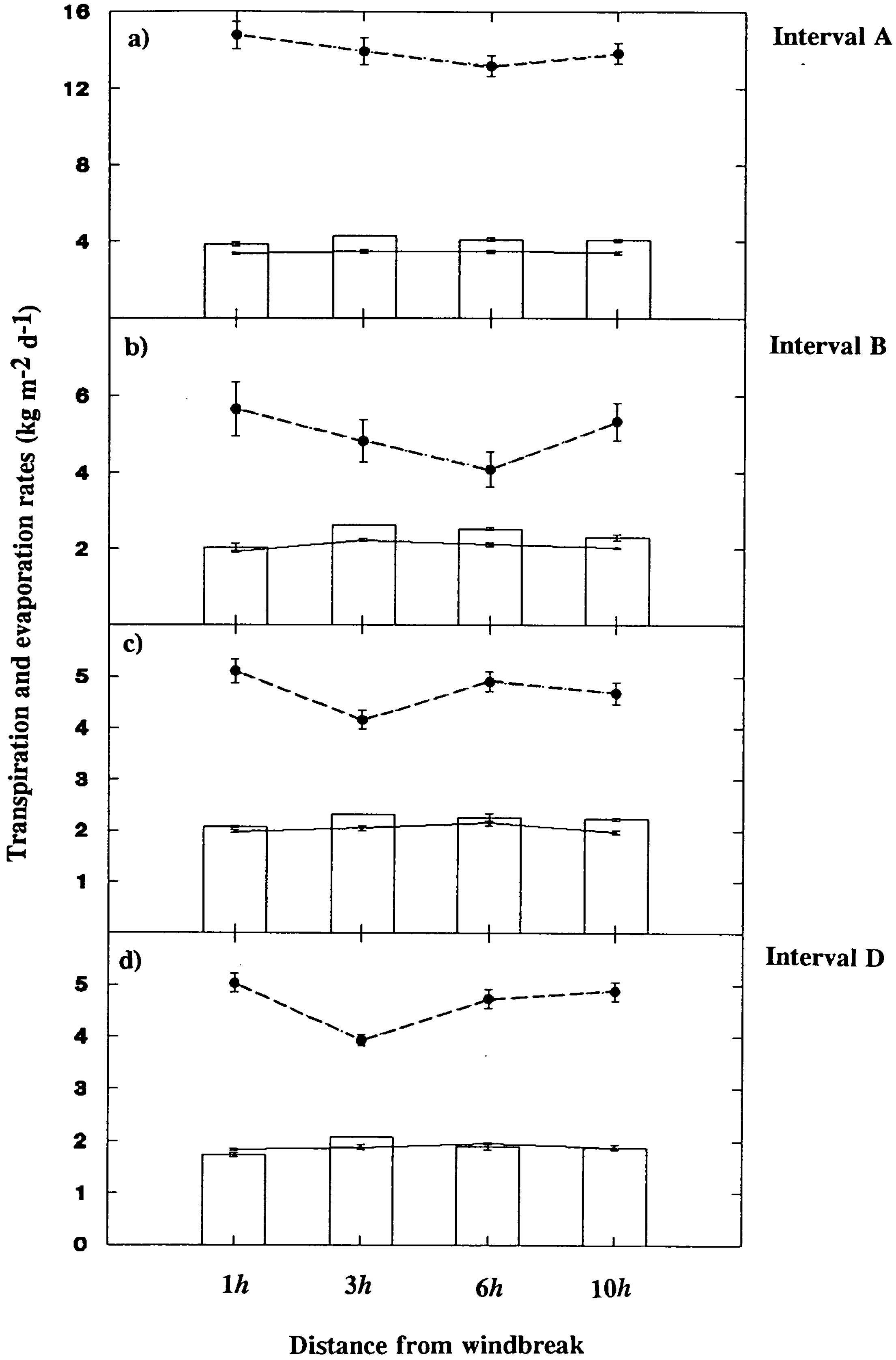


Figure 5.19 Average daily leaf transpiration calculated from eq. 5.15 (▭), with the Penman-Monteith equation (•), and Penman evaporation eq. 5.16 (●) at four distances away from the windbreak, during a) interval A, b) interval B, c) interval C, d) interval D. For details of error bars see text ($n = 4$).

Sheltered areas between 3*h* to 6*h* transpired more, despite having lower evaporation rates per unit leaf area. Decreases in evaporation have been widely documented (Section 5.1.6), however the few direct calculations of transpiration that have been made (Section 5.1.7) show both increases and decreases in transpiration of sheltered plants. Increases in transpiration in shelter under the conditions found here resulted from a combination of higher g_s and T_l which offset any reduction in evaporative demand caused by increased e_a and decreased g_a and R_n.

In the work of Miller *et al.* (1983) the increase in e_a and decrease in g_a was sufficient to offset the increase in g_s and T_l because the system had a large transpiring area and was well watered. As temperatures increase, there may be an increase or decrease in g_s depending on D_{surf}, however transpiration generally increases (Radke and Hagstrom, 1973).

Canopy transpiration (Figure 5.20), was substantially increased in shelter both by increased water use per unit leaf area and increased *L*. The error bars indicate the s.e. between the four days of measurements and not differences between distances from the windbreak.

Table 5.11 Crop water use over the season at different distances from the windbreak (mm d^{-1} ± 1 s.e.), (n = 4).

Interval		Crop Transpiration (mm d^{-1})		
Distance	1*h*	3*h*	6*h*	10*h*
A	0.18 ± 0.01	0.33 ± 0.03	0.17 ± 0.01	0.37 ± 0.02
B	0.32 ± 0.06	0.76 ± 0.13	0.36 ± 0.05	0.58 ± 0.07
C	1.89 ± 0.26	3.67 ± 0.44	2.24 ± 0.33	2.05 ± 0.21
D	3.27 ± 0.11	5.12 ± 0.14	3.87 ± 0.16	3.01 ± 0.32

Values of millet transpiration found in this study Table 5.11, correspond well to

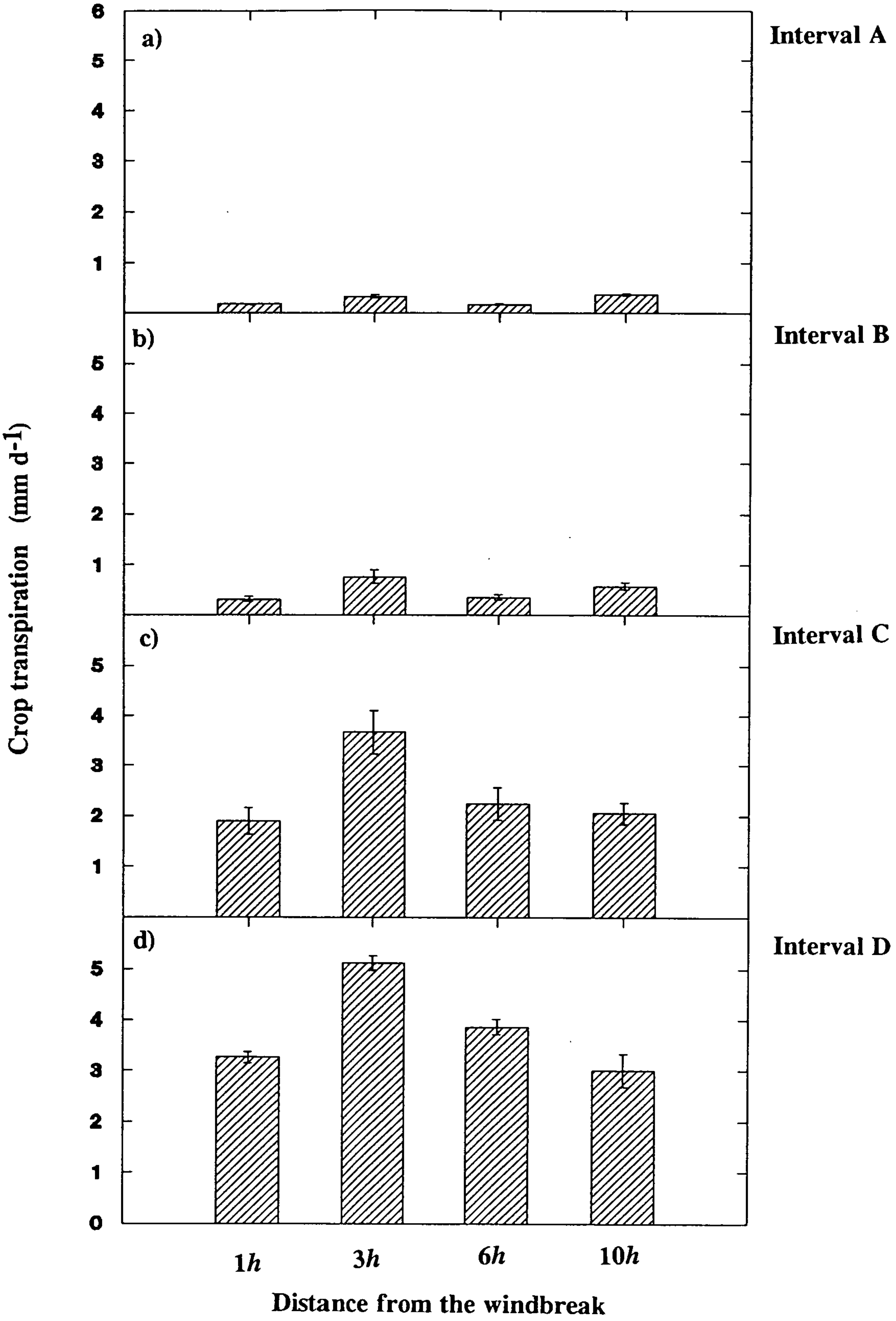


Figure 5.20 Daily crop transpiration with distance from the windbreak during a) interval A, b) interval B, c) interval C, and d) interval D. Error bars indicate ± 1 s.e., ($n = 4$).

those found for millet crops in similar environments (Wallace *et al.*, 1989; Azam-Ali, 1983). Water was thought to have been limiting only at the beginning of 1989, when shelter had an adverse effect on growth. Increased water use in the sheltered area over the rest of the season may not have been detrimental to growth since rainfall was well distributed. Seasonal water use was not determined accurately enough to compare differences in water use efficiency with distance from the windbreak, although it was calculated for comparison with windbreak water use (Section 8.5). However water use efficiency is inversely proportional to D_{surf}, so under conditions that decrease D_{surf} water use efficiency would be expected to increase (Rosenberg *et al.*, 1983).

5.3 SUMMARY OF RESULTS

1) The relationship between R_{n} and S_{t}, and G_{s} and R_{n}, changed with leaf area index, with the seasonal average $\alpha = 0.29$ and $G_{\mathrm{s}} = 0.24R_{\mathrm{n}}$.

2) Radiation was reduced by more than 10 % in a zone ± 5.5 m of the centre of the windbreak. Reduction of radiation at 1*h* on the eastern side of the windbreak only occurred after 16.00 h.

3) The order of day-time air temperatures was $3h > 6h > 10h > 1h$, with temperatures decreasing towards interval C.

4) Leaf temperatures showed no consistent trend with distance from the windbreak, because of the variability of the measurement.

5) e_{a} increased behind a windbreak, being largest in areas of large *L* and small *u*. Differences in D_{a} across the field were small.

6) Calculated soil surface temperatures suggest lethal temperatures may be reached at the beginning of the season, which coulde be increased in areas of shelter.

7) Seasonal conversion coefficients ($\hat{e}$) were 1.76 g MJ^{-1} (1988) and 1.44 g MJ^{-1} (1989), and individual harvest $\hat{e}$ varied with distance from windbreak and stage of

development.

8) Stomatal conductance increased in shelter in the middle of the season, responding to changes in D_{surf}, so when shelter decreased D_{surf} it increased g_s.

9) A negative correlation was found between $\hat{e}$ and D_{surf}, suggesting that part of the variation in $\hat{e}$ was caused by changes in g_s.

10) Transpiration estimated by the Penman-Monteith equation underestimated transpiration while L was low, probably as a result of the heat flux from the soil.

11) Shelter increased transpiration, by both increasing transpiration per unit leaf area and by increasing the leaf area. Shelter decreased Penman potential evaporation.

12) Under non - irrigated Sahelian conditions there is no evidence to support the hypothesis that water is conserved behind a windbreak, although under conditions that decrease D_{surf} water use efficiency may increase. All the above results were obtained assuming advection was not significant.

CHAPTER 6

TREE WATER USE

6.1 INTRODUCTION

Windbreaks have been established extensively in many areas of the Sahel, despite little knowledge of the quantity of water that they will transpire. Windbreak establishment in areas of low rainfall, where the water table is accessible to tree roots, may cause depletion of water reserves, and destabilise the farming system. Where the water table is below the root zone throughout the year the size and effectiveness of the windbreak may be limited by water availability in the dry season.

Windbreak water use has not been widely investigated, particularly in the semi-arid tropics, often because of the difficulty in measuring its transpiration. Recent development of sap flow measuring devices with more sophisticated electronics and theoretical models have lead to a series of improved techniques, (Swanson and Whitfield, 1981; Cohen *et al.*, 1981; Schulze *et al.*, 1985). Use of heat as a tracer for sap flow (heat pulse) and measurement of energy moved by sap flow (heat balance) have lead to more accurate measurements of individual tree transpiration (Cohen *et al.*, 1983; Edwards and Warwick, 1984; Granier, 1987; Cohen, 1991). There then remains the question of how to relate individual tree transpiration measurements to that of the windbreak.

6.1.1 Transpiration

Jarvis and McNaughton (1985) considered transpiration as the weighted sum of two limit conditions, the equilibrium transpiration λE_{eq} (6.1) and the imposed transpiration λE_{imp} (6.2);

$$\lambda E_{eq} = R_n \, \varepsilon \, / \, (\varepsilon + 1) \tag{6.1}$$

$$\lambda E_{imp} = (\rho_a \, C_p / \gamma) \, g_s \, D_a \tag{6.2}$$

where C_p is specific heat capacity of air at constant pressure and $\varepsilon = s/\gamma$. Between these two limits total transpiration λE is given by;

$$\lambda E = \Omega \lambda E_{eq} + (1 - \Omega) \lambda E_{imp} \qquad (6.3)$$

where Ω is a measure of the extent of decoupling of conditions at the leaf surface from conditions in the free air stream, and is given by;

$$\Omega = (\varepsilon + 1)/ (\varepsilon + 1 + g_a/ g_s) \qquad (6.4)$$

Since a windbreak is likely to be well coupled to the atmosphere, Ω will tend to zero and λE will tend to eq. 6.2. The g_{smax} measured for a neem leaf at the beginning of the day was 0.24 cm s^{-1}: Taking the width of neem leaf as 2 cm values of g_a were calculated from eq. IV.12, and gave Ω of 0.30, 0.16, and 0.13 for wind speeds of 0.5, 1.5 and 2.5 m s^{-1}, respectively. In a humid area where D_a is low eq. 6.1 may dominate λE even in well coupled systems, but in the Sahel (using values given in Section 1.3.2.2) $\lambda E_{imp} : \lambda E$ is 0.52, 0.70 and 0.75 for the three wind speeds given above, respectively.

If transpiration from individual leaves is additive, an estimate of tree transpiration can be obtained by multiplying the transpiration of individual leaves (eq. 6.2) by the leaf area of the tree (A_l). If diurnal patterns of $[(\rho_a C_p / \gamma) g_s D_a]$ are relatively constant between trees within a windbreak for a particular time period much of the variability in transpiration between trees may be attributable to A_l. So the transpiration of the windbreak may be calculated by measuring the transpiration of an individual tree and scaling up by the ratio of total leaf area of windbreak to the leaf area of the measured tree.

6.1.2 Relationship between sapwood basal area and leaf area

Linear relationships between sapwood basal area (A_{sw}) and leaf area (A_l) (eq. 6.5) (Marchand, 1983; Whitehead *et al.*, 1984) and between transpiration and sapwood basal area (Kline *et al.*, 1976) have been found in a number of coniferous and broad leaved tree species.

$$A_l = a + b\,A_{sw} \qquad (6.5)$$

where a (m^2) and b (m^2 cm^{-2}) are coefficients of the equation. In young trees where heartwood is a small part of the overall basal area it may be possible to assume $A_{sw} = A_{st}$, where A_{st} is under bark stem basal area.

This chapter presents data on the relationships between leaf area and stem basal area, leaf area distribution in the canopy and the size and growth of the windbreak from 1988 to 1990. The relationships between leaf area, transpiration rate and stem basal area are investigated using a heat pulse velocity technique. These relationships are used to calculate tree and windbreak transpiration over a year.

6.2 MATERIALS AND METHODS

6.2.1 Windbreak description

The windbreaks studied were planted in 1983 as a double row of neem trees (*Azardirachta indica* A. Juss) spaced 2 m between rows and 4 m between trees in a triangular pattern, height distribution is given in Section 6.3.2.1 (see Section 1.8 for more details about the tree).

6.2.2 Leaf area measurements

Defoliation of neem trees was carried out after the rainy season (November to December) in 1988, 1989 and at the end of the dry season in May 1990. Although neem trees retain their foliage throughout the year, there is a marked reduction in leaf area from January to June.

Defoliation in 1988, 1989 and 1990 was combined with measurements of tree height, height to base of canopy and stem diameter at 50 cm. In addition, in 1988 and 1989 stem diameter was measured at 100 cm and 130 cm. Eleven trees were defoliated in 1988, and eighteen trees in 1989 in the post-rainy season (Periods 2 and 3, November to December), and one tree in January 1990. Eight trees were defoliated at the end of the dry season, May 1990. Tree crowns were divided into 4 horizontal layers of equal depth, which were sub-divided into east and west sides of the crown, for all three samplings. All leaves within each of the eight sections were removed, a leaf sub-sample of approximately 5 000 cm^2 was measured using a leaf area meter (Licor 3100, LI-COR Inc., Lincoln NE. USA). Total leaf dry weights of sample and subsample were measured after drying for 48 hours at 70 ^oC.

6.2.3 Tree diameter and height measurements

Stem diameter was measured using a diameter tape accurate to ± 1 mm. Tree height and height to base of canopy was measured using a tree measuring pole, accurate to ± 10 cm. Tree position and extent of branching utilised a 100 m tape measure, accurate to ± 1 cm. Surveys of all the above variables were taken on windbreaks 3a/3b and 3c/3d during December 1988 and March 1990.

Five trees were cut at 50 cm above ground level, and size of growth rings was measured using callipers. Diameter of growth rings 2, 3, 4 and 5 were assumed to equal diameter under bark for the tree at 2, 3, 4 and 5 years, respectively.

6.2.4 Custom heat pulse logger

6.2.4.1 Overview

The Custom heat pulse velocity recorder (Custom Electronics, DSIR Fruit and Trees, Palmerston North, New Zealand) uses the compensation method of Huber and Schmidt (1937) and with a wounding factor calculated using the corrections given by Swanson and Whitfield (1981). Sap velocity varies with direction and depth within the stem (Cohen *et al.*, 1981), so four probes were installed at different depths and directions. Initial tests suggested that the best definition of flow was given when probes were installed between 10 to 55 mm below the bark. Such sap velocity distributions have been found in pine and spruce, with maximum sap velocities found at depths of 20 to 40 mm below the bark because pit membranes near the cambium are imperforate, whereas towards the centre of the tree they become crusted (Mark and Crews, 1973).

The unit allows continuous recording of one set of probes, so the logger was moved every 2 to 7 days between sets of probes installed in different trees over a series of weeks, to sample a range of tree diameters.

The heat pulse technique as developed by Custom Electronics is described as an absolute technique based on the flow of water through a woody matrix of defined properties. Marshall (1958) indicated that sap velocity did not equal heat pulse velocity but could be calculated from it using measurements of volume fractions of water, wood and air in a sample. The technique has been shown to give good agreement with independent methods, such as lysimetry and gas exchange (Custom, 1987; Green and Clothier, 1988). Comparison of the technique with a small, cut off *Leucaena leucocephela* tree in water in India gave agreement of within 10 % (Brenner, 1987). However, Green and Clothier (1988) by applying a pressure gradient across a piece of Kiwi-fruit stem found that a factor of 1.6 was needed to correct for wounding, whereas apple trees gave good direct agreement between sap flow measured directly and that measured with the heat pulse. The discrepancy for Kiwi-fruit was thought to be caused by the large diameter of the xylem vessels and the large distance between vessels (0.1 to 0.8 mm).

6.2.4.2 Wounding factor and night-time sap flow

The introduction of a probe into the woody matrix causes an interruption of the sap flow in that area, effectively adding more inert material and slowing the heat pulse. Swanson and Whitfield (1981) modelled the effect of different probe spacings and constructions on heat flow and provided a set of tables of the correction that should be applied to compensate for wounding.

A section of sapwood taken from a neem stem was photographed under a compound microscope (Figure 6.1). The wide spacing of the xylem vessels, caused a change in the wounding factor. The average distance between xylem vessels and a series of random transects superimposed on the photograph was 0.3 mm which was considered as an additional wounding factor and added to the original wounding factor (usually 1.8 mm). The average width of xylem vessels was 90 ± 8.3 μm, which compared well with that found by Nair (1988) for neem in India, but the average xylem density (16.6 ± 1.0 elements mm^{-2}) was lower.

Measured night-time sap flows are often ignored (Edwards and Warwick, 1984; Cohen, 1991). However, night-time transpiration may occur (Rawson and Clarke, 1988) or night-time sap flows may be important in terms of rehydration of stem tissue. An error may be introduced into the calculation of night-time sap flow by the returning of an over-range time when there was no flow, resulting in the calculation of a small flux. In order to eliminate the possibility of an over-range error from zero sap fluxes, times were weighted logarithmically, decreasing the importance of slower times. Modifications outlined above have been used in the sap flow calculations.

6.2.5 Comparison of techniques

A series of methods were compared to the heat pulse;

1) Cut off tree technique, (Landsberg *et al.*, 1976)
2) Calculation of transpiration from canopy conductance using a porometer and micrometeorological variables (eq 5.15) (Jones, 1983).
3) Heat balance gauges (Baker and Van Bavel, 1987).

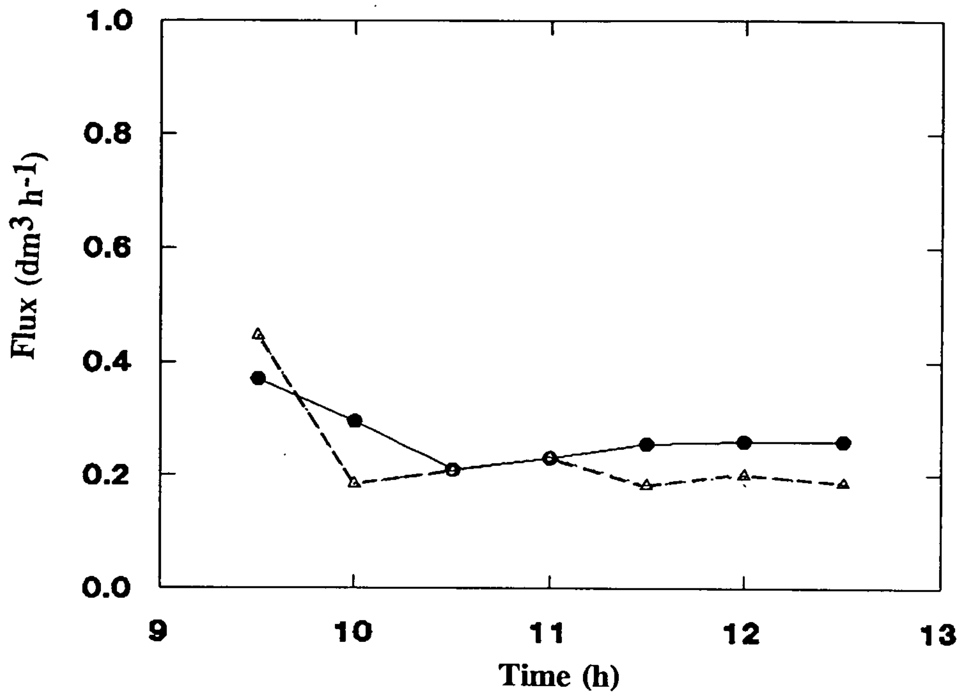
6.2.5.1 Cut off tree technique

Cutting a tree stem under water has been used successfully on pines (Roberts, 1977), and apple trees (Landsberg *et al.*, 1976). Comparisons between the heat pulse and the cut off tree made in December 1989, February 1990 and November 1990 showed that sap flow declined rapidly after cutting under water, probably as a result of cavitation of xylem vessels (Figure 6.2). This prevented a comparison of the two methods at the larger flow rates more characteristic of uncut neem trees.

6.2.5.2 Calculated values of transpiration using a porometer

A comparison was carried out on a small 2-year-old neem tree ($A_l = 4.5$ m^2) in November 1990. Stomatal conductances were measured on both sides of 20 leaves using a null balance porometer (Licor 1600, LI-COR Inc., Lincoln, NE. USA). Leaf temperatures were measured using thermocouples (Section 3.2.9) and air vapour pressure with a ventilated psychrometer (Section 3.2.4). E was calculated from equation 5.15., and A_l obtained from defoliation (Section 6.2.2). Transpiration measured with the heat pulse compared well to that calculated with equation 5.15 (Figure 6.3). Values using the uncorrected wounding factor underestimated the sap flux.

Figure 6.2 Sap flux in a cut-off neem tree measured with a measuring cylinder as uptake from water filled bucket (●), and by a heat pulse velocity recorder (△), in December 1989.



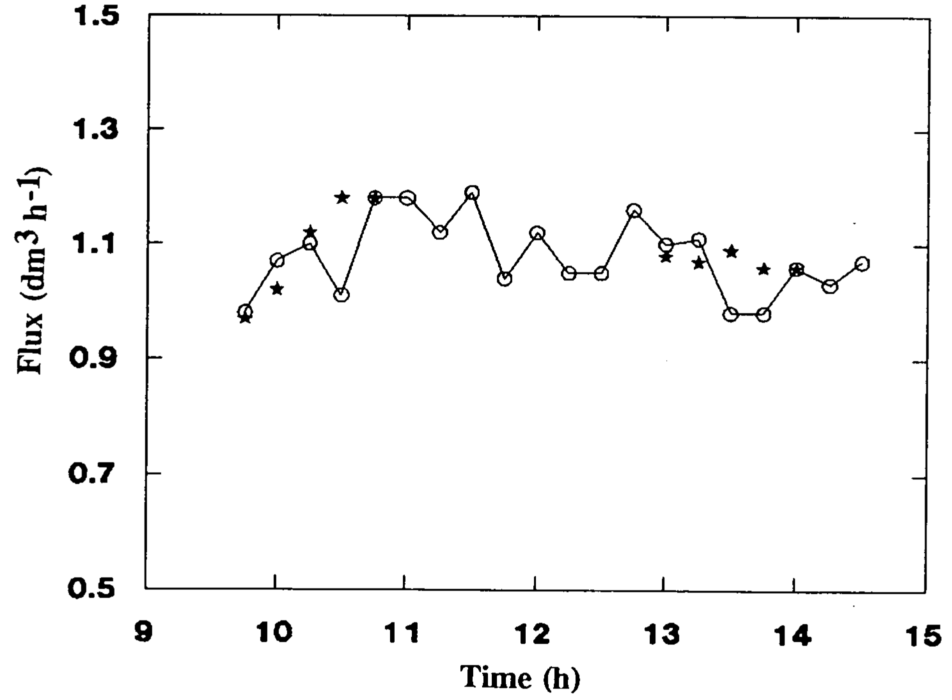


Figure 6.3 Calculated transpiration from leaves of a neem tree (★), compared to sap flux measured by a heat pulse velocity recorder (○), in November 1990.

6.2.5.3 Heat balance method

Transpiration rates measured by heat balance gauges (SGB35-WS, Dynamax, Houston, Texas) were compared to measurements from the heat pulse in December 1990. A heat balance gauge was installed 50 cm upstream of a heat pulse unit on a 42 mm diameter branch of a neem tree. A time series plot over two days (Figure 6.4) indicated higher measured fluxes by the heat balance in the morning relative to the heat pulse, however in the afternoon differences were reversed. Measured total day-time flux was about 10 % higher with the heat pulse than the heat balance, with results showing a substantial hysteresis between the two methods (Figure 6.5). The heat balance method has three potential sources of error, as follows:

i) Zero night-time flow is assumed, to allow calculation of conductivity of the sheath (the material wrapped around the gauge to prevent heat loss to atmosphere); this will decrease average readings.

ii) During the night there is a energy build-up at the heater so that when sap starts to flow in the morning there is a large signal peak, giving anomalous readings, suggesting that readings before 10.30 h may be overestimates.

iii) Calculated flux is inversely proportional to measured temperature difference so at the high flow rates that occurred a small error in a small temperature difference may cause a large error in estimate of sap flow.

The heat pulse method would be expected to underestimate transpiration in the morning, and overestimate in the afternoon, resulting from a net loss of water from storage in the plant at the beginning of the day, and a net gain in the evening and during the night (Landsberg, *et al.*, 1976). Although this may also be the case with the two stem flow methods the magnitude of the hysteresis was larger than would be expected.

6.2.6 Sampling strategy

Fourteen trees were sampled over the period 10/7/89 to 14/3/90. Details of sampling dates and tree sizes are given in Table 6.1. Measurements were grouped into time periods:

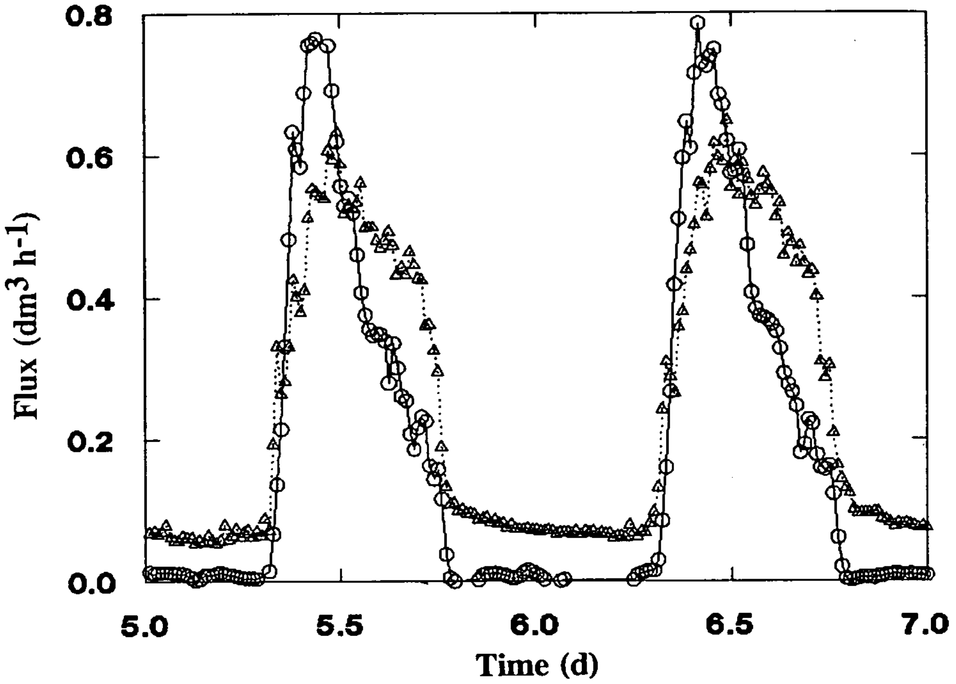


Figure 6.4 A time series plot of sap flow within a branch of a neem tree measured with a heat balance gauge (○), and a heat pulse velocity recorder (△), in December 1990.

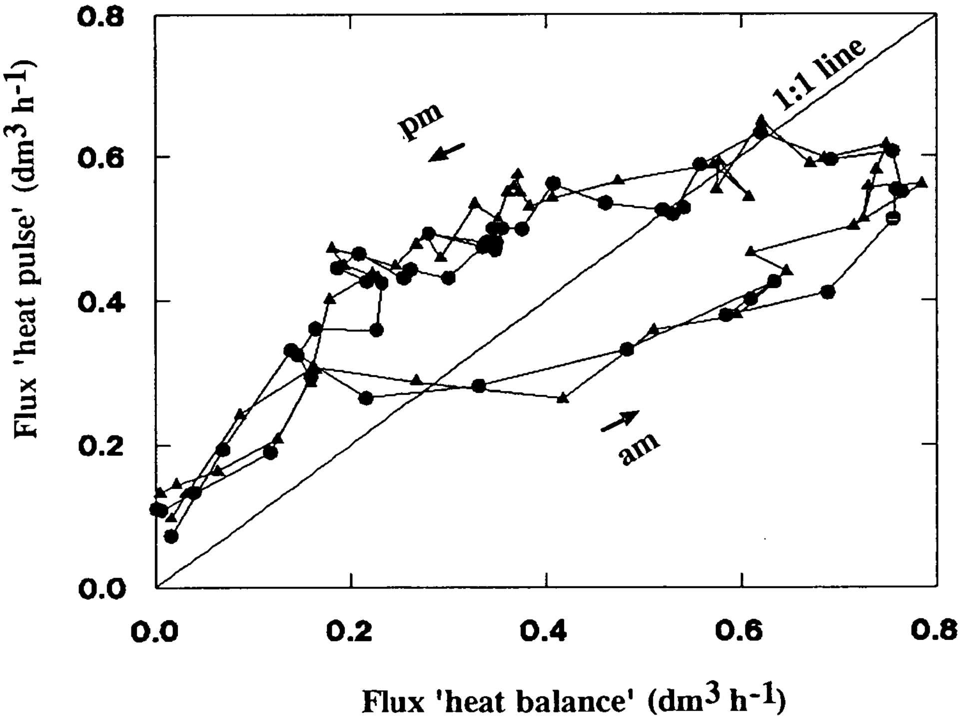


Figure 6.5 A comparison between sap fluxes measured with the heat pulse and heat balance methods for a branch of a neem tree over two days, Day I (●), Day II (▲). The straight line is a 1:1.

Period 1 : rainy season; was subdivided to correspond to the time intervals A, C and F (Chapters 4 and 5, see Table 4.1).

Period 2 : post-rainy season; 25/11 - 9/12

Period 3 : post-rainy season; 13/1 - 30/1

Period 4 : dry season; 13/2 - 14/3.

Table 6.1 Sampling dates and tree sizes for the heat pulse measurements.

Tree no	Year	Date	Diameter (cm)*	A_{st} (cm^2)+	Period
1	1989	10/7-17/7	13.3	124.07	Int. A
2		28/8-7/9	11.0	77.48	Int. C
3		28/10-29/10	12.2	94.96	Int. F
4		19/10-20/10	11.3	91.69	Int. F
5		29/11	15.6	154.40	2
6		25/11	7.9	40.70	2
7		9/12-12/12	11.1	75.07	2
8	1990	13/1-14/1	15.0	142.74	3
9		18/1	7.0	32.30	3
10		23/1-30/1	13.2	110.90	3
11		13/2-18/2	14.1	126.32	4
12		6/3-12/3	16.6	174.47	(4)^
13		6/3-11/3	15.8	158.21	4
14		6/3-12/3	12.3	96.49	4

* - Diameters are under bark diameters at the height of heat pulse installation which was 80 cm above the ground in all trees except tree 1 which was 100 cm.

\+ - A_{st} was calculated at 130 cm above the ground.

^ - Tree 12 was not used in the final analysis, because the deepest probe showed no decrease in sap flux. This meant that the sap velocity polynomial fitted by the programme did not decrease towards the centre of the tree, leading to very high calculated sap fluxes probably overestimating actual sap flow.

6.3 RESULTS

6.3.1 Leaf area

6.3.1.1 Leaf area vs. stem basal area

A_l was regressed against A_{st} at three heights (Table 6.2). No significant differences were found between post-rainy season 1988 and 1989 relationships (Figure 6.6). The linear relationship between A_l and A_{st} at 130 cm had a non-significant intercept and a significant positive slope. A better correlation when using A_{st} at a height of 130 cm, rather than at 50 cm, may result from $A_{sw} = A_{st}$ at 130 cm rather than at 50 cm. Figure 6.7 shows the linear relationships between A_l and A_{st} at 50 cm in both dry and post-rainy seasons. Differences in slopes of the two lines were not significant giving a combined slope of 0.260, but the intercepts were significantly different at the 1 % level.

Table 6.2 Regression coefficients for the relationship between leaf area (A_l) and stem basal area (A_{st}), $A_l = a + b\,A_{st}$.

Variable	height	1988	1989	1988/89	1990
b	50	0.356	0.255	0.273	0.237
	100	0.434	0.415	0.396	
	130	0.464	0.445	0.429	
a	50	-3.86	-9.624	5.303	-12.806
	100	-2.71	-5.717	-1.860	
	130	-1.14	-3.656	-0.580	
r^2	50	0.630	0.605	0.700	0.971
	100	0.760	0.736	0.801	
	130	0.702	0.835	0.865	

6.3.1.2 Leaf area distribution

Distribution of leaf area within the crowns was analysed for all defoliated trees. Fractions of leaf area contained within each layer did not vary significantly with the total leaf area of the crown in 1988, 1989 or 1990. Leaf areas of layers 1 and

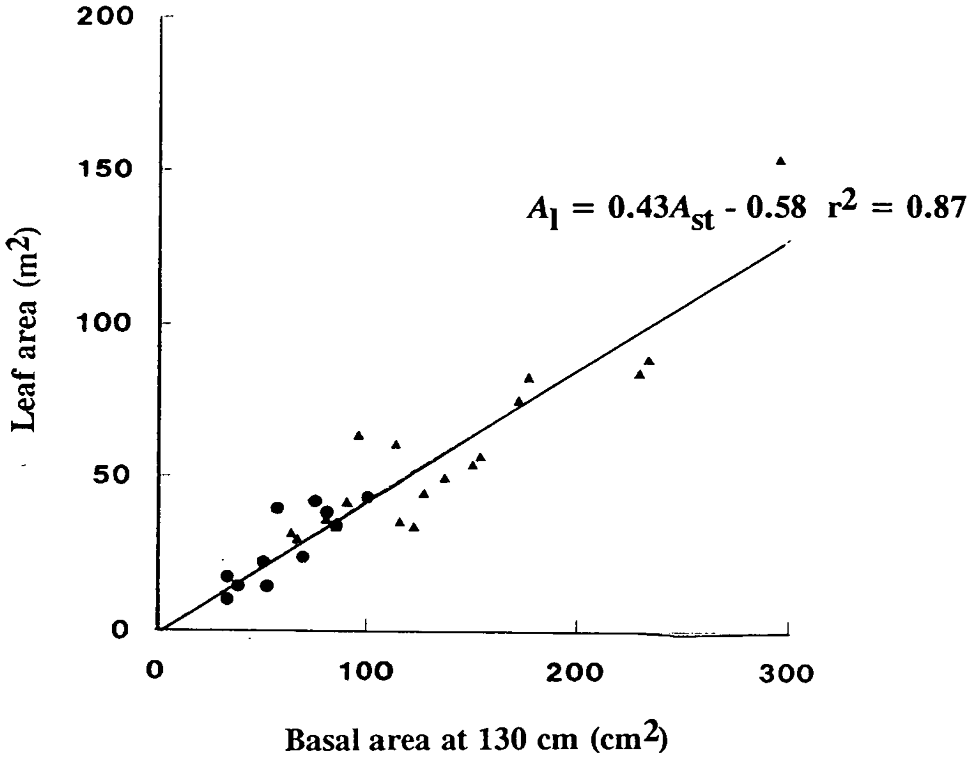


Figure 6.6 The relationship between tree leaf area and stem basal area at 130 cm for neem trees defoliated in the post-rainy season 1988 (●), and 1989 (▲).

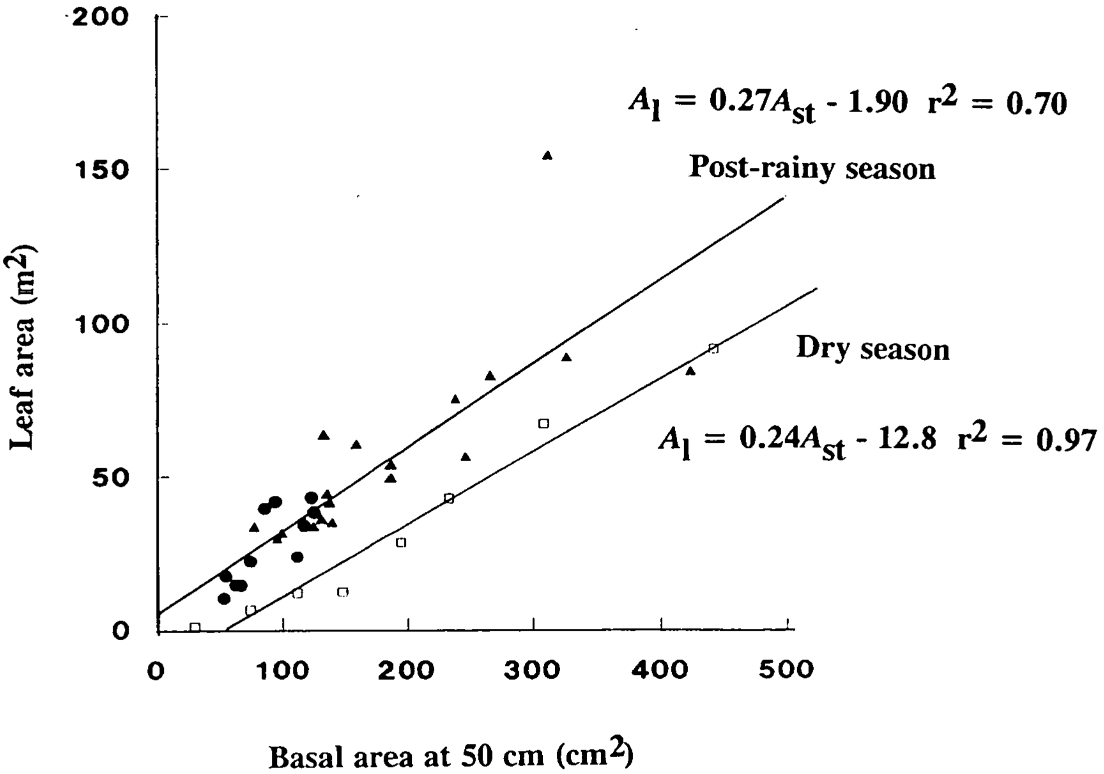


Figure 6.7 The realtionship between tree leaf area and stem basal area at 50 cm for neem trees defoliated in the post-rainy season 1988 (●), 1989 (▲), and dry season 1990 (☐).

4, and 2 and 3 were similar (Figure 6.8a). Measurements of the dimensions of the crown (Figure 6.8b), allowed calculation of crown volume, and the volume of each section, assuming uniformity in the direction of the windbreak (ie. a 2 dimensional system). Relative leaf area density was calculated by dividing the fractional leaf area by the fractional volume occupied by the leaf area for each layer (Figure 6.8c). Trees showed larger leaf area on their exposed side than their shaded side (Figure 6.9).

6.3.2 Measurements of windbreak trees

6.3.2.1 Tree heights and diameters

Average tree heights and basal areas of two windbreaks 3a/3b and 3c/3d for 1988 and 1989 are shown in Table 6.3.

Table 6.3 Average height and stem basal area of neem trees within a windbreak.

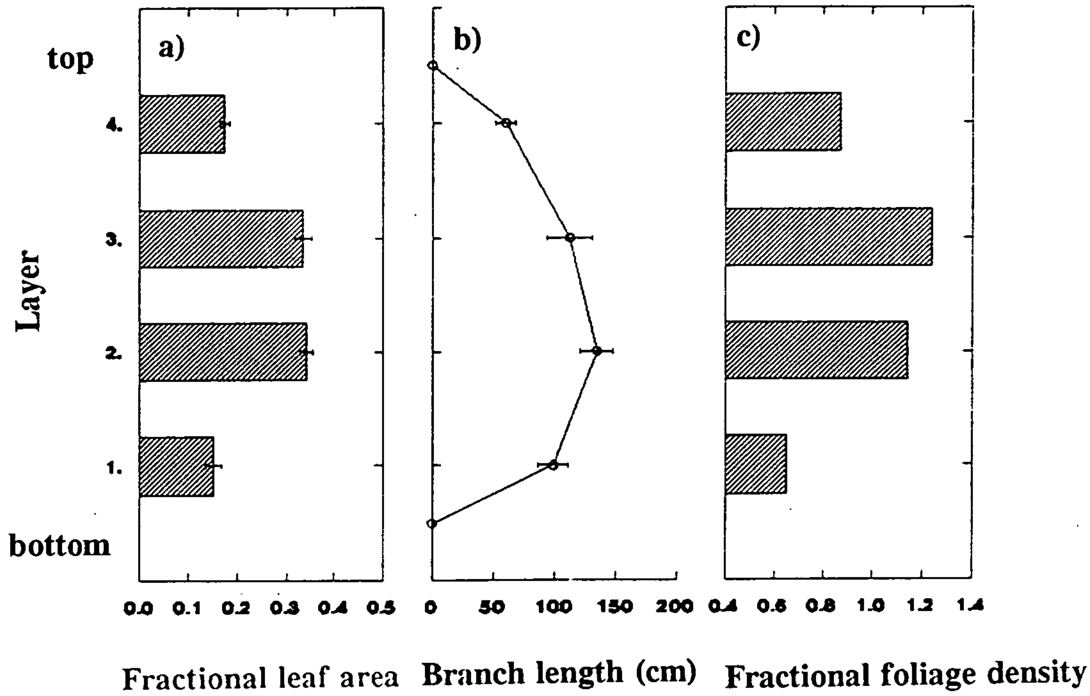
Windbreak	3a/3b		3c/3d		s.e.
	1988	1989	1988	1989	(n = 95)
Number of trees	94	94	98	95	
Height mean (m)	6.2	6.7	6.5	7.1	0.1
A_{st} at 130 cm (cm^2 $tree^{-1}$)	94.7	143.2	93.5	136.6	7.25

Distribution of h and A_{st} at 130 cm for windbreak 3a/3b in 1988 and 1989 are shown in Figures 6.10a - d. Heights had a normal distribution, however, stem basal area distribution was skewed.

6.3.2.2 Change of tree basal area with age

A_{st} of the five sample trees cut down in 1988 were calculated from the diameter of their growth rings for years 5, 4, 3 and 2. Each sample tree was assigned to a size class from the frequency distribution (Figure 6.10c), according to its A_{st} at year 5. The fractional decrease in A_{st} at years 4, 3 and 2 were calculated for each sample tree and assigned to its size class. Size classes without a sample tree were assigned

Figure 6.8 a) Fractional distribution of foliage with height in post-rainy season neem trees. b) Measured average branch lengths of outer branches in neem trees. c) Foliage density calculated by dividing the fractional leaf distribution by the fractional volume it occupies. Error bars indicate ± 1 s.e., (n = 30)



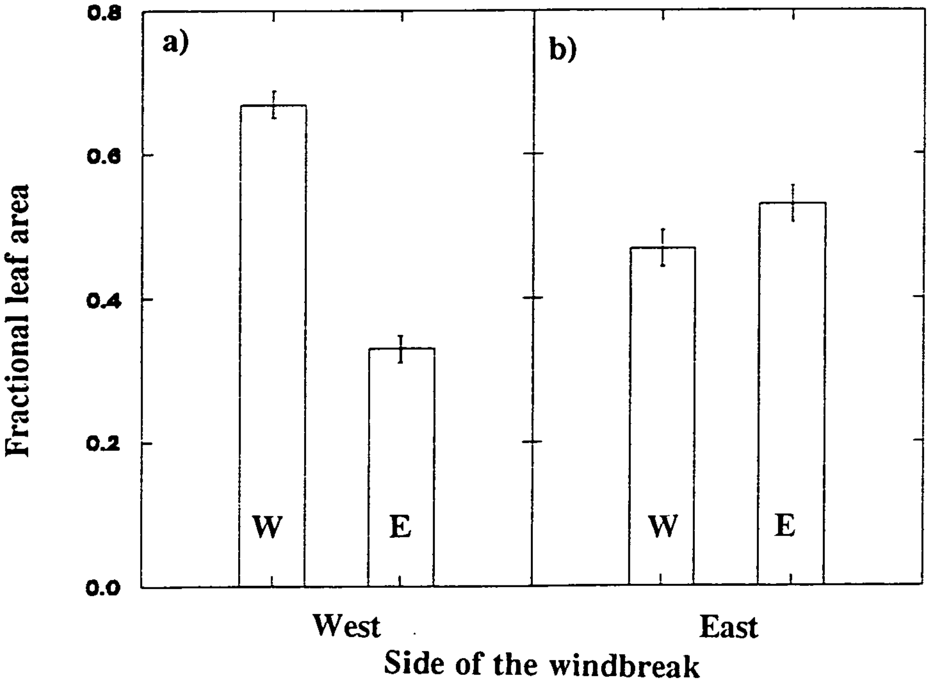


Figure 6.9 Leaf distribution of windbreak trees on the west a) and east b) sides of the windbreak. Foliage on the tree was divided into east 'E' and west 'W' sides of the tree. Error bars indicate ± 1 s.e. (n = 30)

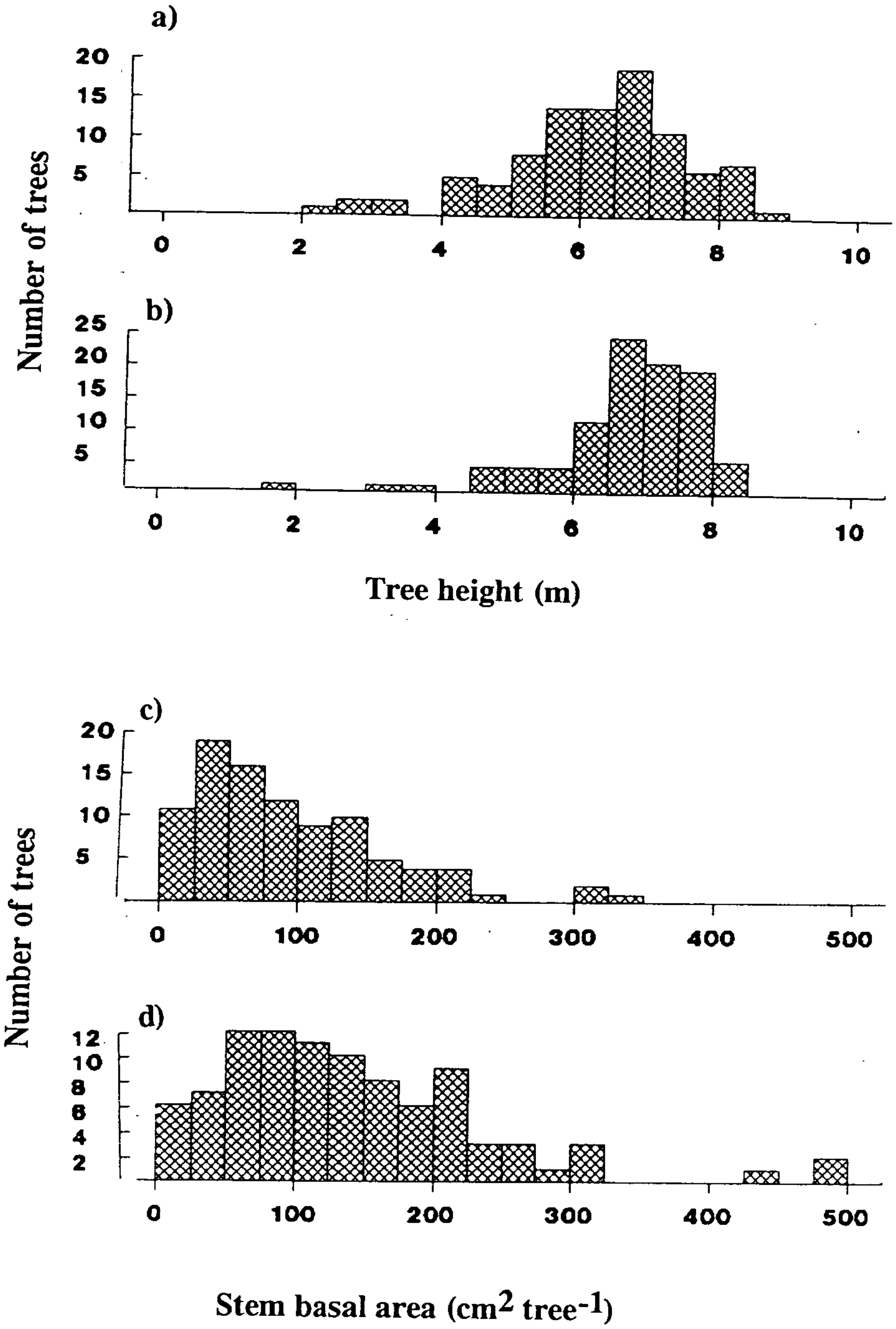


Figure 6.10 Frequency distributions of trees on windbreak 3a/3b, a) 1988 height distribution, b) 1989 height distribution, c) 1988 stem basal area distribution, d) 1989 stem basal area distribution.

a fractional decrease in A_{st}, equal to that of the size class nearest to it. The A_{st} for the mid-point of each size class was calculated for years 5, 4, 3 and 2, and multiplied by the class frequency. All classes were summed giving a total A_{st} for the windbreak at years 4, 3 and 2. When this approximation was compared to measured total A_{st} at 5 years the error was 0.9 %. Average tree A_{st} for years 2 to 6 are given in Table 6.4

Table 6.4 Average A_{st} per windbreak tree calculated and measured for years 2 to 6 at a height of 130 cm

Year	2	3	4	5	6
A_{st}	12.1	48.2	69.1	94.7	143.2
(cm^2 $tree^{-1}$)	cal	cal	cal	meas	meas

cal = calculated meas = measured

6.3.3 Sap flux data

The variation between tree sap fluxes (Figure 6.11a) was reduced when fluxes were normalized with respect to A_{st} at 130 cm, (Figure 6.11b). Average daily and maximum sap fluxes normalized to A_{st} and A_l for each period, (see Table 6.1) are presented in Table 6.5a - b.

Table 6.5a Sap fluxes for neem trees normalized with respect to A_{st}.

Period	Daily flux (dm^3 d^{-1} m^{-2}) Mean	1 s.e.		Max. hourly flux(dm^3 h^{-1} m^{-2}) Mean	1 s.e.
Period 1 Int. A	3714			314	
Period 1 Int. C	2645			228	
Period 1 Int. F	4151	911	(n = 2)	349	84
Period 2	3113	132	(n = 3)	221	1
Period 3	2237	279	(n = 3)	170	14
Period 4	2177	173	(n = 3)	140	12

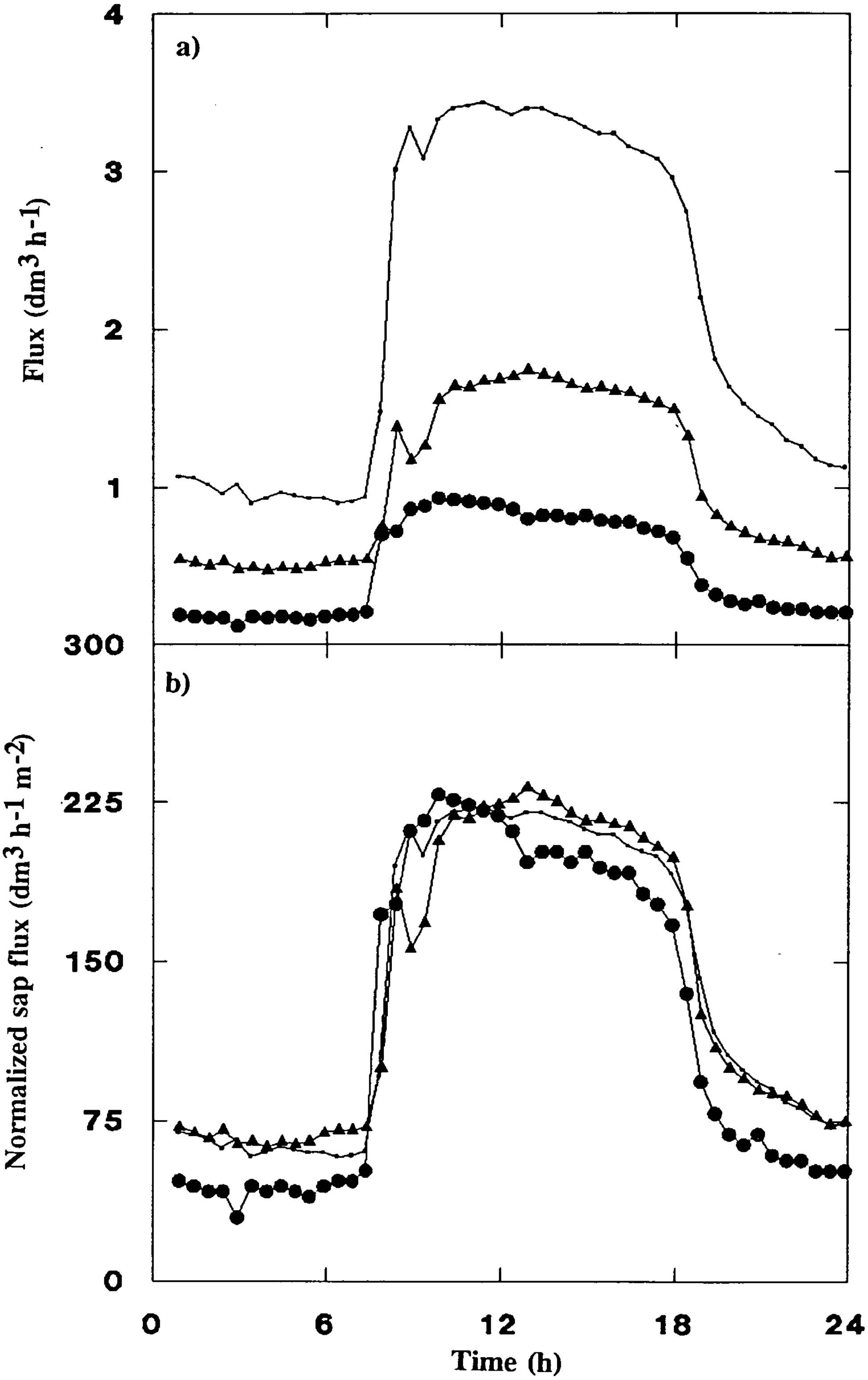


Figure 6.11 a) Diurnal sap fluxes for three trees during period 2, tree 5 (•), tree 6 (●), tree 7 (▲). b) Sap fluxes normalized to stem basal area at 130 cm for trees as above.

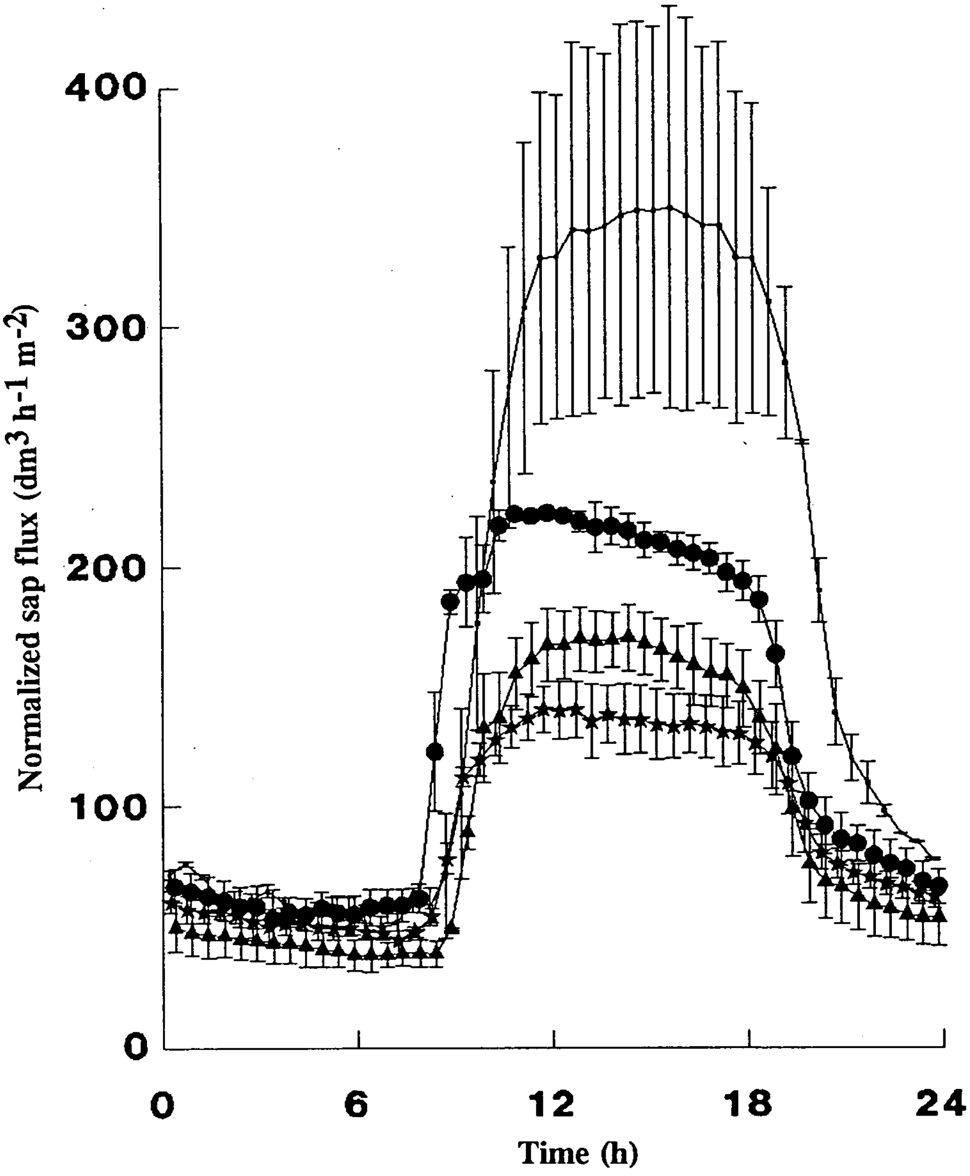


Figure 6.12 Average sap fluxes normalized to stem basal area at 130 cm, for interval F (•) (n = 2), period 2 (●) (n = 3), period 3 (▲) (n = 3), and period 4 (★) (n = 3). Error bars indicate ± 1 s.e.

Table 6.5b Sap fluxes for neem trees normalized with respect to A_l.

Period	Daily flux (dm^3 d^{-1} m^{-2})			Max. hourly flux (dm^3 h^{-1} m^{-2})	
	Mean	1 s.e.		Mean	1 s.e.
Period 1 Int. A	0.8751			0.0741	
Period 1 Int. C	0.5563			0.0542	
Period 1 Int. F	0.9815	0.2185	(n = 2)	0.0827	0.0200
Period 2	0.7397	0.0269	(n = 3)	0.0528	0.0003
Period 3	0.5333	0.0692	(n = 3)	0.0405	0.0035
Period 4	0.5133	0.0404	(n = 3)	0.0330	0.0027

Significant decreases in day-time flux occurred between period 1 interval F and period 4 (Figure 6.12). Daily flux decreased by 25 %, 28 %, and 3 % from interval F to period 2, periods 2 to 3, and 3 to 4 respectively.

At the start of the rainy season (interval A) the soil profile was dry, D_a was high during the day and the trees had relatively small leaf areas (Figure 6.13, tree 1). As the season progressed (interval C), D_a decreased, and the soil profile became wet (Figure 6.13, tree 2), by the end of the season the soil profile had dried out (interval F), D_a increased, and leaf area was high, (Figure 6.13, tree 3 and 4). Night-time sap flux may have resulted from both loss of water through leaves at night, via g_s or g_c and rehydration of dehydrated stem and leaf tissues. Night-time sap flow was lowest when the system was wet and atmospheric demand was low (interval C, tree 2). All other measurements were taken when the soil was dry and indicate considerable night-time flow.

6.3.4 Windbreak transpiration

The average A_{st} of the windbreak trees (Table 6.4) combined with the average daily sap flux of the windbreak trees normalized with respect to A_{st} (Table 6.5) gave the average sap flux per windbreak tree for 24 hours. Daily sap fluxes correspond better to daily transpiration rates than hourly sap fluxes to hourly

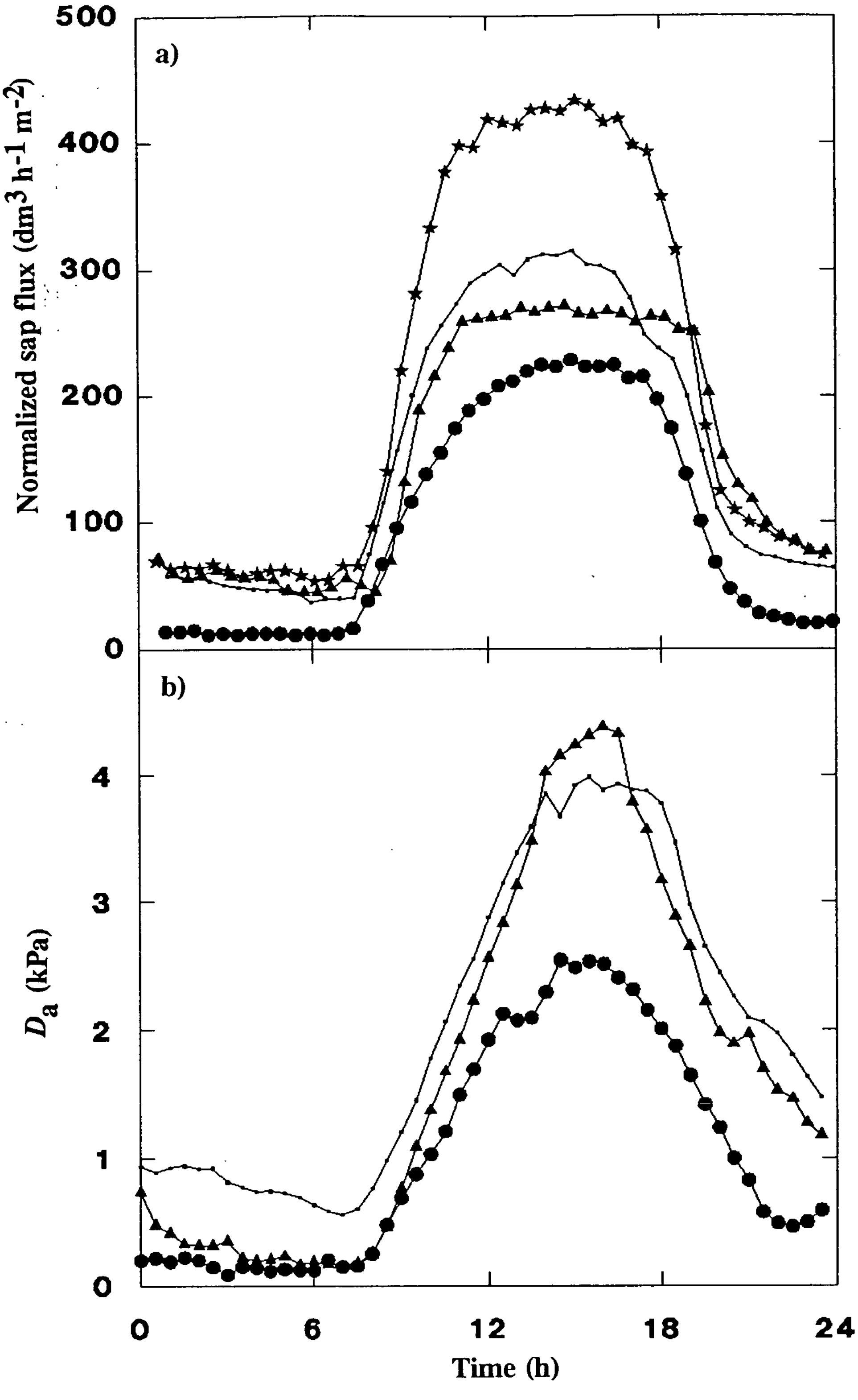


Figure 6.13 a) Sap fluxes normalized with respect to stem basal area at 130 cm for period 1, tree 1 (•), tree 2 (●), tree 3 (▲), and tree 4 (★). b) Corresponding values of D_a to the sap fluxes in a) trees 3 and 4 had the same D_a (▲).

transpiration rates, since daily changes in tissue water content are likely to be smaller than hourly changes, and close to zero.

The windbreak consisted of a double row of trees spaced at 4 x 2 m, equivalent to 0.5 trees per m windbreak. The canopy extended between 1.0 to 2.5 m from the line of the windbreak, little shading occurred beyond 2.5 m at midday (Figure 5.5), and millet was sown 2.0 to 3.0 m from the line of the windbreak. Taking canopy extension as 2.5 m, 1 m of windbreak would occupy 7 m^2 of land.

Table 6.6 presents the transpiration of a 5 and 6 year old windbreak per unit length of windbreak, on an assumed ground area and assuming the relationship between transpiration and A_{st} found for 1989 - 90 was relevant for 1988 - 89. Transpiration for younger windbreaks can be evaluated in a similar manner.

Table 6.6 Transpiration of a 5 and 6 year old windbreak over 6 months of the year

	Average calculated daily transpiration			
	1988	1989	1988	1989
Period	(dm^3 d^{-1} (m windbreak)$^{-1}$)		(mm d^{-1})	
Int. A	17.59	26.59	2.51	3.80
Int. C	12.53	18.94	1.79	2.71
Int. F	19.66	29.72	2.81	4.25
Period 2	14.74	22.29	2.11	3.18
Period 3	10.59	16.02	1.51	2.29
Period 4	10.31	15.59	1.47	2.23

Comparison can now be made with millet transpiration rates given in Chapter 5. However, after the cropping season the system of windbreaks spaced 100 m apart would have a transpiration rate of only 0.300, 0.223, 0.160, and 0.156 mm d^{-1} for interval F, periods 2, 3 and 4, respectively.

6.4 DISCUSSION

6.4.1 Leaf area/basal area relationship

Linear relationships between A_{sw} and A_l have been found by Kaufmann and Troendle (1981) with the slope of the regression (*b*) varying from 1.88 with subalpine fir (*Abies lasiocarpa*) to 0.19 in aspen (*Populus tremuloides*). Marchand (1983) found values of 0.67 for balsam fir (*Abies balsamifera*), and for red spruce (*Picea rubens*) of 0.17, lower than those of Kaufmann and Troendle (1981). Whitehead and Jarvis (1981) suggest that a wide range of *b* would be expected, since it is dependent on species, age, site and permeability of the wood. Some of the variability for values of *b* may be accounted for by differences in wood permeability (Whitehead *et al.*, 1984). Climate may also influence *b* since the higher the average transpiration at a site, the smaller the leaf area supplied per unit sapwood basal area. Whitehead *et al.* (1981) found $b = 0.65$ for a mature teak plantation in Nigeria. In the present study $b = 0.43$ and may be related to lower rainfall or difference between species: *b* would be expected to be lower under more arid conditions (Whitehead and Jarvis, 1981). In a more mature neem windbreak, A_{sw} rather than A_{st} would be required for estimates of *b*, since heartwood was already significant at a height of 50 cm, as indicated by the values of r^2 (Table 6.2).

6.4.2 Tree Capacitance

Woody tissues act as water storage organs as well as organs for water transport, with water moving out of storage in the early part of the day and being replenished from the root system towards the end of the day and during the night. Changes in tissue water content has been observed in terms of the shrinking and swelling of plant tissue (eg. leaves, stems and roots; Kozlowski, 1972), and changes in stem water content (Waring *et al.*, 1979; Brough *et al.*, 1986). Chaney (1981) calculated that water depletion of the stem may supply water for 12.2 hours of transpiration in temperate hardwoods. Waring *et al.* (1979) estimated that at high planting densities of Scots pine (*Pinus sylvestris*) 30 - 50 % of the transpired water could be extracted from the stem sapwood. Many studies of the relationship between leaf water potential and transpiration have shown hysteresis (Jarvis, 1976; Lassoie *et al.*, 1977; Brough *et al.*, 1986; Landsberg *et al.*, 1976), although Cohen *et al.* (1983) showed little hysteresis in citrus even at low soil water potentials. The lag of water absorption via roots behind transpiration was halved by the removal of the root system in tree seedlings (Satoo, 1962), suggesting that the roots and soil constitute a major resistance to water flow (Running, 1980; Whitehead and Jarvis, 1981). Capacitance increases with increasing tree size (Lassoie *et al.*, 1977), increasing water stress (Granier, 1987) and varies with species (Schulze *et al.*, 1985). Sap flux measurements made on *Guiera sengalensis* in Niger during the rainy season showed a rapid response of sap flow to changes in solar radiation, suggesting low capacitance, with small well-watered trees. The larger neem trees however showed substantial night-time sap flow, except during interval C when evaporative demand was low and soil water potentials were high, ie. the potential gradient within the soil-plant-atmosphere continuum was small and the plant unstressed.

Close agreement between the heat pulse and calculated fluxes (Section 6.2.5.2) was only achieved when using a small 2-year-old neem tree at the beginning of the dry season. The small size of the tree would have reduced the capacitance since it had a young root system, and little tissue to dehydrate. Estimation of average leaf conductance and leaf temperature would also be improved, because a larger fraction of the canopy was being sampled than with larger trees. Measurements of water potential within the soil-plant-atmosphere continuum are needed to establish the exact nature of resistances and degree of capacitance within the system.

6.4.3 Tree transpiration

6.4.3.1 Sapwood basal area basis

Sapwood basal area has been used to scale up from a series of individual tree measurements to a forest canopy in both temperate coniferous stands (Kline *et al.*, 1976), and tropical rain forests (Jordan and Kline, 1977). Jordan and Kline (1977) suggested that transpiration was related to sapwood area within a tropical rain forest and that the relationship was not improved when soil type and species were considered. Normalized measurements are useful as a scaling factor, however, they are of limited value for comparison with other literature.

6.4.3.2 Leaf area basis

Sap fluxes normalized to leaf area enable easier comparisons with similar work. Average maximum hourly sap fluxes per unit leaf area of a neem windbreak were 0.054, 0.083, 0.053, 0.041, and 0.033 dm^3 h^{-1} m^{-2} for interval C (rainy season), interval F (start of dry season), periods 2, 3 (warm-dry season), and 4 (hot-dry season) respectively (Table 6.6). These values are based on the assumption that the actual leaf area did not significantly differ from the leaf area calculated from the regressions in Section 6.3.1.1. Doley (1981) presented tables of leaf transpiration per unit area for semi-arid trees and shrubs, divided into species from the Cerrado (750 - 1000 mm) and the drier Caatinga (500 - 750 mm) of north Brazil. Some Cerrado species had higher normalized transpiration rates of 0.09 to 0.11 dm^3 h^{-1} m^{-2} than found in this study, often because of lower stomatal control (maximum transpiration occurred at the same time as maximum D_a). *Anacardium occidentale*, *Curatella americana* and *Eucalyptus saligna* had rates of 0.059, 0.056 and 0.064 dm^3 h^{-1} m^{-2} in the late dry season, with maximum transpiration occurring early in the day. The late dry season transpiration rates of 0.041 and 0.033 found for neem may be underestimates, because of overestimates of A_l in the hot-dry season or because of the large tree capacitance. Transpiration rates of *Jatropha phyllacantha* in the Caatinga zone decreased from 0.090 to 0.069 to 0.048 dm^3 h^{-1} m^{-2} from the early to middle to late dry season, similar to those found for neem. Leaves from *Maytenus rigida* showed decreases of 0.079, 0.052, 0.041 dm^3 h^{-1} m^{-2} over the same time period.

6.4.4 Control of Transpiration

Differences during interval F between trees 3 and 4 suggested a stomatal response influenced more by plant water status than atmospheric demand, since trees 3 and 4 were measured at the same time of year however tree 3 had a flat topped sap flux curve (Figure 6.13) when compared to the round topped curve of tree 4. This may be the result of differences in soil water supply for the two trees affecting stomatal conductance.

The control of transpiration may be as a direct effect of leaf water potential or, as has been recently suggested, by root signals (Davies and Zhang, 1991). Stomata often act to maintain steady transpiration rates over the day despite increases in evaporative demand, possibly, to avoid catastrophic xylem cavitation (Tyree and Sperry, 1989; Jones and Sutherland, 1991). Meinzer and Grantz (1990) suggested that stomatal conductance changes to maintain leaf water potentials within a limited range, over a wide range of external conditions, and this supports the idea that it is soil or root water potential that is controlling stomatal conductance rather than leaf water status.

Doley (1981) listed transpiration rates of arid zone shrubs that exceeded those in semi-arid areas, *Acacia radiana* doubling its rainy season transpiration in the dry season, and *Salvadora persica* and *Boscia senegalensis* having transpiration rates of 0.188 and 0.354 $dm^3\ h^{-1}\ m^{-2}$, respectively, because they had access to a water table. The implications for tree transpiration of tree root access to water tables have not been fully investigated. However, if under arid conditions soil or root water status rather than leaf water status or atmospheric conditions controls stomatal conductance and thus transpiration (as Doley's data suggests), the transpiration rate of a windbreak rooting into a water table would be considerably larger than the transpiration rates found here.

The strong coupling of windbreaks to their environment means that transpiration rates are proportional to tree leaf areas. These in turn are related to sapwood basal areas, so that measurements of individual tree transpiration can be scaled up to a windbreak using total A_{sw}. This simple approach to calculating tree transpiration should be applicable to many tree species and within a variety of agroforestry systems.

6.5 SUMMARY OF RESULTS

1) There was a linear relationship between stem basal area and leaf area of neem trees in a windbreak

2) The relationship changed over the season, but remained linear with the same slope but a different intercept.

3) Variation in sap flux between trees could be accounted for by their difference in leaf area (via stem basal area).

4) Normalized sap fluxes were combined with measurements of windbreak stem basal area to calculate transpiration of a windbreak over 9 months of the year.

5) Water use of a 6-year-old windbreak was 26.6, 18.9, 29.7, 22.3, 16.0, 15.6 dm^3 day^{-1} (m windbreak)$^{-1}$, for the start of the rainy season, mid-rainy season, post-rainy season, warm-dry season, late-warm-dry season, and hot-dry season, respectively. These figures correspond to a range of 1.5 to 4.3 mm d^{-1}, on the basis of crown projected area.

CHAPTER 7

WINDBREAK - CROP COMPETITION

7.1 INTRODUCTION

Reduction of crop yields near trees is often the most noticeable interaction between tree and crop in a windbreak system. Any increase in yield caused by shelter may be counteracted by yield losses from land occupied by the windbreak, from adjacent area not planted and from competition between trees and crop (Bates, 1911; Stoeckler, 1962; Kort, 1988). Quantification of these losses in agronomic and economic terms is important in evaluating the benefit of windbreaks within a farming system.

Reduction of soil temperature by shading (Shankarnarayan *et al.*, 1987), increased water and nutrient availability from canopy drip, and leaf fall may all lead to increases in crop production near trees (Kellman, 1979; Belsky *et al.*, 1989), but discussion here is limited to competitive interactions between trees and crop.

Yield reduction near windbreaks usually results from a combination of above-ground competition (light) and below-ground competition (water and nutrients), and is often expressed in relation to windbreak height, even though use of the limiting resource by trees is related to crown size and so may be better correlated with stem basal area or to leaf area (Section 6.3.1.1). In some studies yields have been normalized with respect to yields at a distance 3*h* from the windbreak (eg. Kort, 1988) but this may overestimate competition, since plants at 3*h* often yield more than unsheltered fields (Chapter 2).

7.1.1 Above ground competition

Shading generally reduces crop yields by reducing the PAR available for crop photosynthesis (Monteith, 1972), although some forest understorey crops such as cardamom (*Amomum subulatum*) and cocoa (*Theobroma cacao*) suffer photoinhibition in high quantum flux densities and so grow better under shade trees

(Singh *et al.*, 1989; Fassbender *et al.*, 1991). High quantum flux densities may damage plant leaves (Krause, 1988) and reduce the quality and quantity of the marketable product (Rylski, 1986). Photosynthesis of leaves of many C3 species saturate at moderate quantum fluxes (1000 μmol m^{-2} s^{-1}) (Ludlow, 1983), so a unit reduction in PAR at high quantum fluxes (2000 μmol m^{-2} s^{-1}) reduces photosynthesis less than the same reduction at low quantum fluxes (500 μmol m^{-2} s^{-1}). Photosynthesis of C4 cereals rarely becomes light saturated (Jones, 1983), so shading of maize and millet generally reduces yields (Bates, 1911).

Growth of crops are generally linearly related to the PAR intercepted (Section 5.2.4). The relationship between PAR and total solar radiation is quite well known above canopies (eq. 5.1), although it varies with cloudiness and humidity, but below a canopy the relationship is less certain. PAR is preferentially absorbed by the pigments in leaves, so that transmission of PAR through a canopy is less than that of the full spectrum of solar radiation. Marshall and Willey (1983) used equation 7.1 to modify measured transmissivities for solar radiation (t_s) to transmissivity for PAR (t_{par}).

$$\ln(t_{par}) = 1.4 \ln(t_s) \qquad (7.1)$$

This equation enables the calculation of the amount of PAR transmitted by a tree crown, from measurements of transmissivities of solar radiation (Section 5.2.2.1).

7.1.2 Below ground competition

Competition for water and nutrients may occur in soil horizons exploited by both tree and crop root systems. Reductions of crop yield are generally small at distances exceeding 2*h* from the windbreak (Kort, 1988; Lyles *et al.*, 1984; Bates, 1911), but in dry areas yield reductions have been observed out to 4.6*h* (Greb and Black, 1961).

The degree of competition depends upon the relative distribution of tree and crop root systems. Observed yield reductions corresponded well to the measured extent of tree roots, with conifers often less competitive than broad leaves (Bates, 1911; Greb and Black, 1961). Rooting densities are usually highest in the uppermost soil horizons although the proportion of the root system in the upper horizons, varies with species and soil conditions. Yeager (1935) showed that 90 % of roots for 31 temperate tree species from the Great Plains were concentrated in the top 90 cm of soil, with an average ratio of the lateral spread of roots to the height of the tree of 1.3. Cereals crops have a similar vertical distribution, with an even greater proportion of their roots contained in the top 30 cm of the soil (ODA, 1987a; Payne *et al.*, 1990).

Many semi-arid trees develop deep roots, eg. *Faidherbia albida* rooted to a depth of 3 m in 9 months in Niger, (Van Den Beldt, personal communication), and 18 month old *Prosopis cineraria* rooted below 1.7 m in India (Shankarnarayan *et al.*, 1987). This may allow trees to access resources not available to crops, especially important in the presence of a water table. However, having deep roots has little effect on competition if growth resources are concentrated in the surface soil layers. Prajapati *et al.* (1971) showed yield reductions of sorghum up to 4.5*h* from a row of *Prosopis juliflora* DC. corresponding to the extent and density of *Prosopis* roots.

7.1.3 Comparisons of above- and below-ground competition

Root pruning has been recommended as a windbreak management practice (Stoeckler, 1962; Read, 1964; Singh and Dayal, 1975; Kort, 1988), and has been shown to eliminate adverse effects of windbreaks of five tree species in the Great Plains, increasing yield within 3*h* of the windbreak by up to 50 % (Lyles *et al.*, 1984). Root pruning of Siberian elm (*Ulmus pumila*) and Osage orange (*Maclura pomifera*) reduced the extent of competition from 2*h* to 0.5*h* and from 2.2*h* to 1.4*h*, respectively (Bates, 1911; Stoeckler, 1962), suggesting that below ground competition predominated on the Great Plains, and that there was little effect of shading.

It would seem reasonable to assume that competition for the most limiting growth resource predominates. Competition for light may be similar from year to year, whereas competition for water and nutrients varies with rainfall and soil fertility, although availability of water and nutrients indirectly affect competition for light.

7.1.4 Allelopathy

Growth reductions near a windbreak may also result from allelopathy, the inhibition of growth of one species caused by toxic chemicals from leaves, litter or roots of the other. Allelopathic inhibition of crop growth has been shown to exist with walnut (*Juglans nigra*), juniper (*Juniperus* spp.), oaks (*Quercus* spp.) and *Eucalyptus baxteri*, *E. globulus* and *E. camaldulensis* (Rice, 1984). Many of the inhibitory substances, such as salicylic acid and terpenes, derive from the leaf litter and leach into the soil. The degree of inhibition of crop growth depends upon the soil, and the sensitivity of the crop to inhibition. Generally, on free draining sandy soils, allelopathy is less important than on badly drained clay soils (Rice, 1984). Yield reductions near windbreaks resulting from allelopathy are difficult to separate from the effects of competition, and have not been attempted in the field.

This chapter investigates the magnitude and causes of yield reductions near the windbreaks, using data from Chapters 2, 5 and 6. Methods and set up of the field trial 'Competition' are given in Section 2.2.4 and Figure 2.4a - b.

7.2 RESULTS

7.2.1 Final harvest data from trial 'Competition'

7.2.1.1 Results 1988

No significant differences in grain and stover yields were found in the vicinity of root-pruned (pruned) and control (unpruned) windbreaks, (Figures 7.1a - c). No decrease of yield occurred near the windbreak. Lower stover weight at 0.6*h* and higher harvest index near the unpruned windbreak were not significantly different from values near the root-pruned windbreak.

7.2.1.2 Results 1989

Yield reductions did not extend beyond 10 m (1.7*h*) in 1989 (Figures 7.1d - f), with reduction in panicle weight close to both windbreaks resulting from fewer panicles and not from lower grain weight per panicle, apart from at 0.5*h*. The

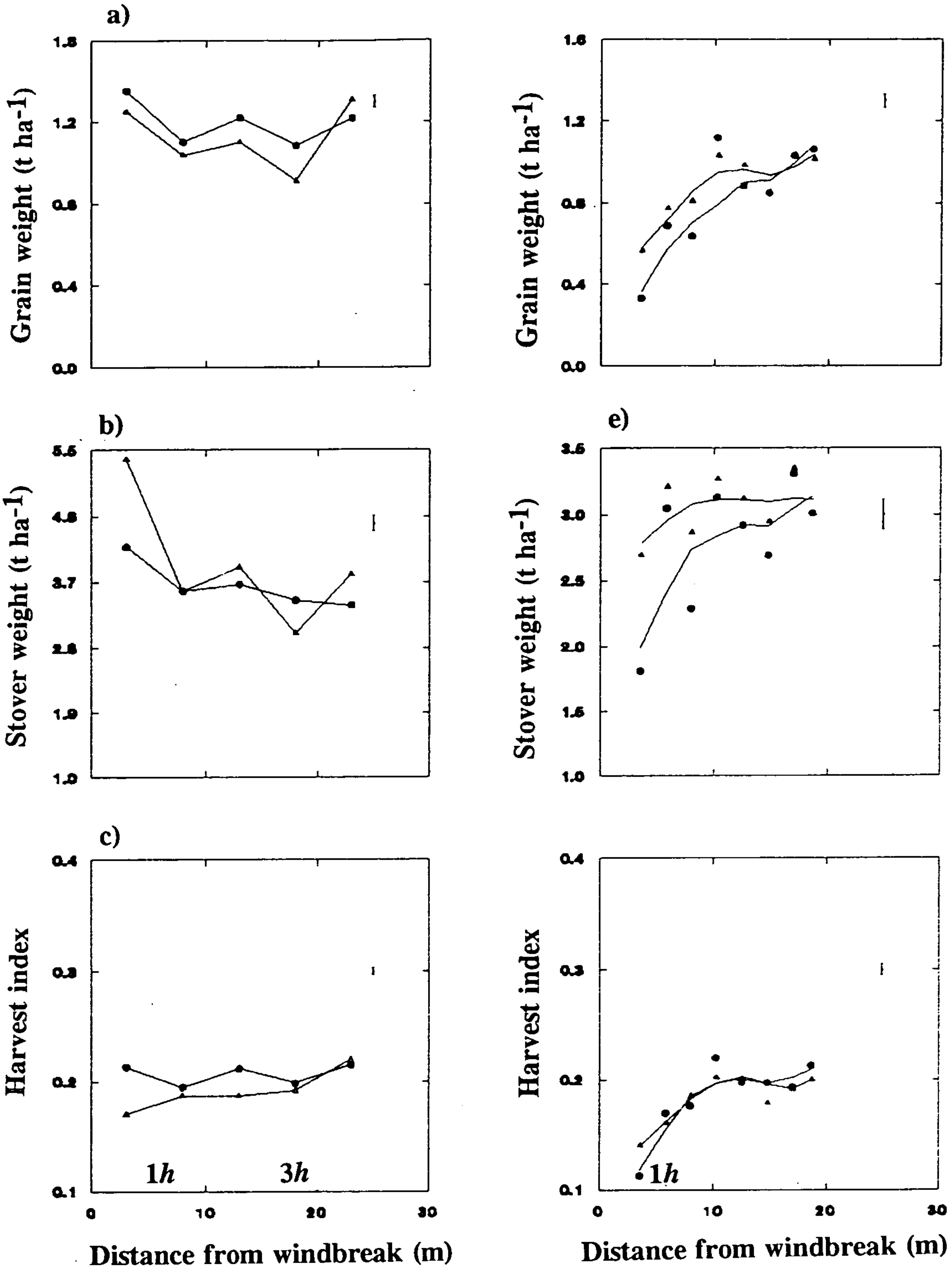


Figure 7.1 Final harvest grain and stover yields for trial 'Competition' for 1988 and 1989. Millet growing next to root-pruned windbreaks (▲) and unpruned windbreaks (●), a) grain yield 1988, b) stover yield 1988, c) harvest index 1988, d) grain yield 1989, e) stover yield 1989 and f) harvest index 1989. The error bars indicate ± 1 s.e.

difference in grain weight averaged over 1.5*h* from the root-pruned and unpruned windbreaks was 0.166 t ha^{-1}. Grain weight per panicle was consistently higher on the root-pruned plots, with 1000 grain weight showing no response to treatment or distance.

Stover weight averaged over a distance 0.5*h* to 1.5*h* from the windbreak was 0.54 t ha^{-1} larger in the vicinity of the root pruned windbreak than close to the unpruned windbreak (Figure 7.1e), although harvest indices for both treatments were similar (Figure 7.1f). Harvest index decreased towards the windbreak on both the pruned and unpruned windbreak. The differences in millet growth adjacent to pruned and unpruned windbreaks were not significant at the 5 % level, when analysed by curve fitting or using paired and unpaired t-tests (see Section 2.3).

Table 7.1 Percentage yield reduction averaged over the zone of competition (3.5 m to 10.2 m; 0.5*h* - 1.7*h*) relative to the average yield between 10.2 m to 18.6 m (1.7*h* - 3.1*h*) from the windbreak, with and without root pruning of the windbreak.

	unpruned	root-pruned	difference
Grain	45 %	28 %	17 %
Stover	27 %	13 %	14 %

Above-ground competition was taken as the reduction of crop yield in the vicinity of the pruned windbreak. If crop yield reduction near the unpruned windbreak results from a combination of above and below-ground competition, below-ground competition can be taken as the difference between the pruned and unpruned yield reductions. Table 7.1 shows that competition reduced grain yields more than stover yields. Yield reductions for stover were equally attributable to above and below-ground competition, but grain yields were reduced more as a result of above than below-ground competition.

7.2.2 Competition data from all three trials

Normalizing final harvest data from 'Standard' (Section 2.4.2), 'Density' (Section 2.4.3) and 'Competition' (Section 7.2.1) trials to yield at 3*h*, gave similar results for all three trials and both sides of the windbreak. Table 7.2 contains the average of these three trials and indicates that competition reduced grain weight more than stover weight, but did not extend beyond 10 m on any of the trials.

Table 7.2 Grain and stover yields at final harvest for both sides of the windbreak with distance from the windbreak for all trials in 1989, normalized to 3*h*.

			Yields normalized to 3*h*			
Distance (m)		Grain	s.e.	(*n* = 5)	Stover	s.e.
3.50	0.6*h*	0.36	0.03		0.60	0.03
5.75	1.0*h*	0.68	0.05		0.89	0.06
8.00	1.3*h*	0.88	0.08		0.94	0.07
10.25	1.7*h*	1.04	0.04		0.99	0.02

7.2.3 Competition for light

Measurements of average daily t_s (Figure 5.5), were used in eq. 7.1. to calculate equivalent t_{par} with distance from the windbreak. Measurements of t_s were taken during November and December, and would differ from the pattern of t_{par} in June to September (rainy season). The influence of time of year on t_{par} was estimated using a light interception model (Wang and Jarvis, 1990). Differences between t_{par} during the rainy season and post-rainy season did not exceed 10 % for the area planted with millet.

Millet yields at a distance x from the unpruned windbreak were normalized to the millet yield at 3*h* (Y_u), as were millet yields at distance x from the pruned windbreak (Y_p). Using equation 7.2a and b, the normalized millet yield expected if only above- or below-ground competition existed can be calculated.

$$\text{Above-ground competition} = Y_p \tag{7.2a}$$

$$\text{Below-ground competition} = (1 - (Y_p - Y_u)) \tag{7.2b}$$

The reduction in R_{par} parallels the reduction in stover yield (Figure 7.2b), but not the reduction in grain yield (Figure 7.2a). The zone of competition marked by the two vertical dotted lines appears to be similar for both above- and below-ground competition, with below-ground competition having similar effects on stover and grain.

7.2.4 Competition for water

7.2.4.1 Soil water extraction

Methods : Measurement of soil water content near the trees using a neutron probe was prevented by constant instrument failure over the season during both years. Towards the end of 1989 a series of soil water profiles were taken by extraction of 30 cm soil cores at 1*h*, 3*h*, 6*h* and 10*h* using a 3 cm diameter soil auger. Soil cores were weighed and dried at 100 ^oC for 48 hours and then re-weighed.

Results : A profile of soil water content for 23/10/89 (Figure 7.3), at the end of the cropping season, shows lower water content at depth (1.0 - 1.8 m) close to the windbreak compared to that in the centre of the field. This indicates extraction of water by deep tree roots from below the root zone exploited by the crop. The vertical dotted line indicates the water content for the permanent wilting point determined in the laboratory (Bley, 1990).

7.2.4.2 Transpiration

Whether tree and millet extract water from the same horizons during the rainy season is not known, but if total windbreak transpiration (E_w) is less (on a land area basis) than millet transpiration (E_m), the millet crop may experience less competition for water from the windbreak than it would from an adjacent area of millet, assuming that soil evaporation is not significant in either case. Although this approach is simplistic since there will be occasions when $E_w > E_m$ and competition for water might not be important, because of water extraction from different horizons, it is usful for comparison of E_w and E_m over the season.

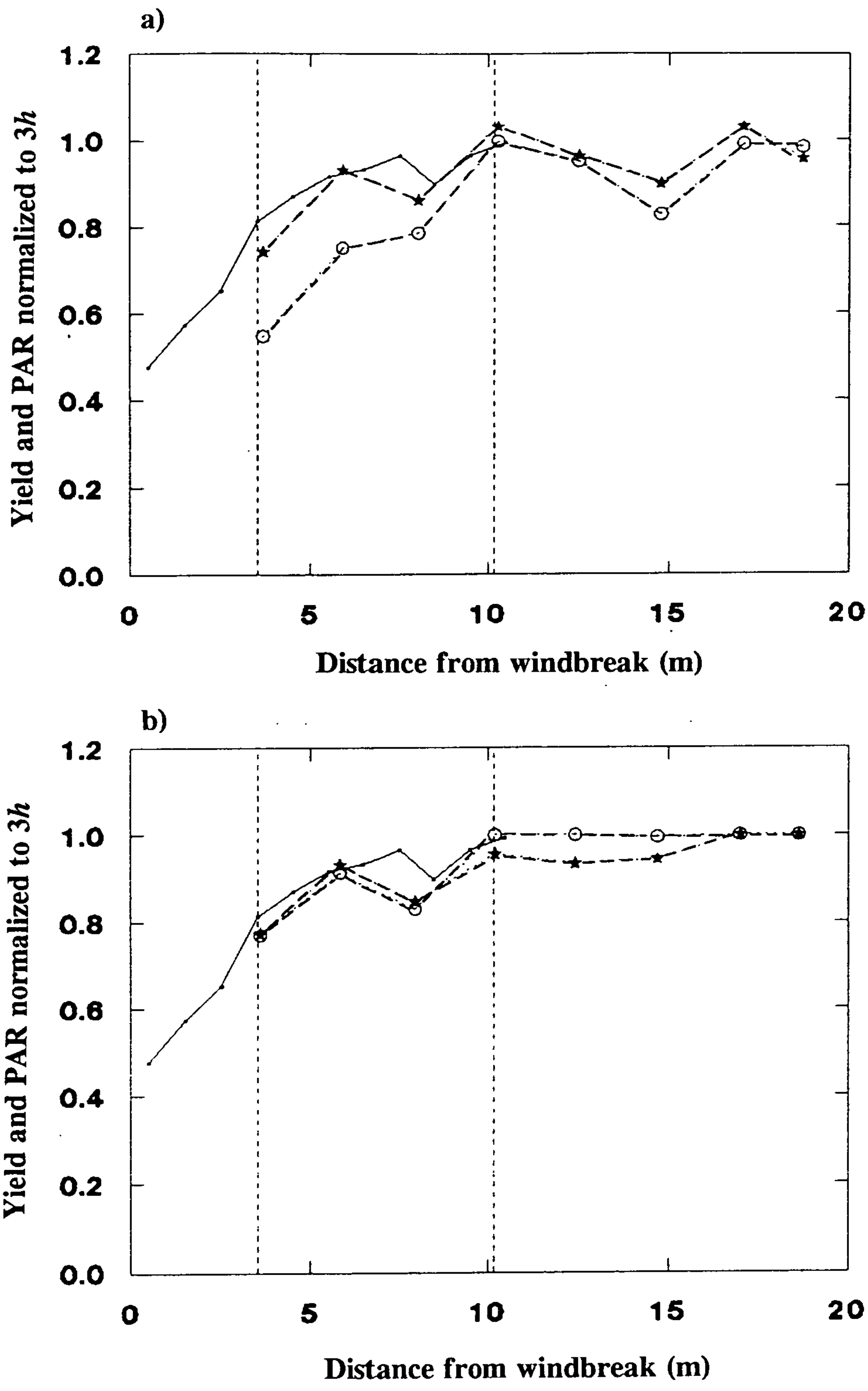


Figure 7.2 Yield reduction relative to yield at 3*h* of stover (★), and grain (o), attributable to: a) above-ground competition, and b) below-ground competition. Reduction in average daily R_{par} (—). The vertical lines indicate the boundary of the zone of competition.

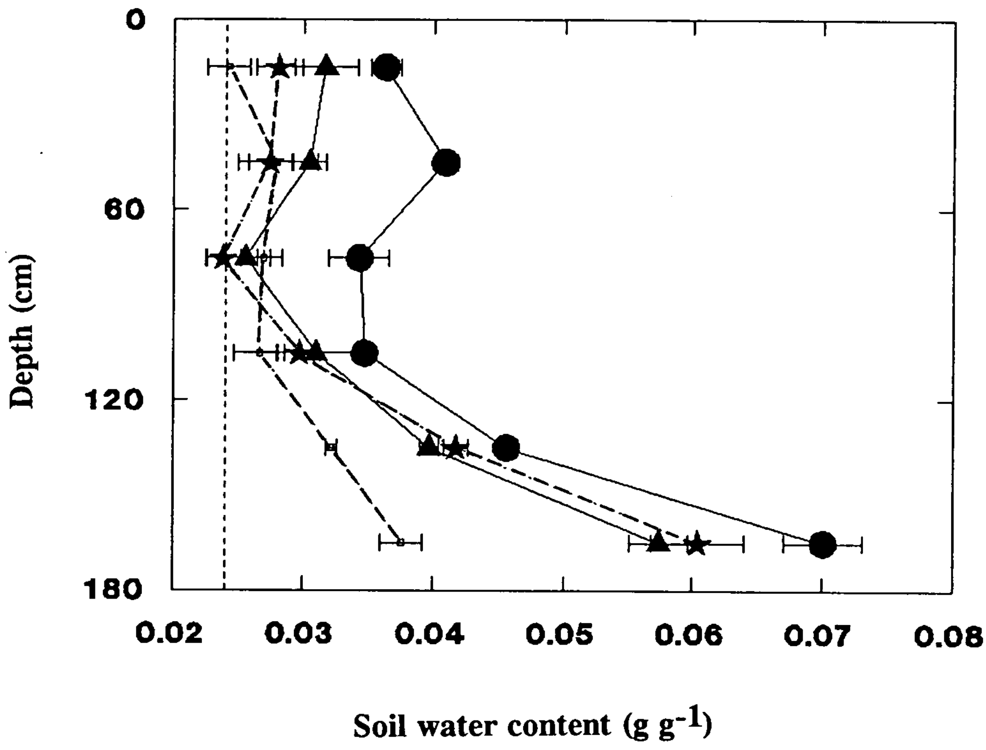


Figure 7.3 Gravimetrically measured soil water contents at the end of the season, at distances of 1*h* (•), 3*h* (●), 6*h* (▲), and 10*h* (★) from the windbreak. The dotted vertical line indicates permanent wilting point, and error bars indicate ± 1 s.e.

Assuming that water was extracted by both trees and crops from the same soil horizons (Figure 7.4, compiled from Figure 5.20 and Table 6.6), suggests that E_w was much larger than E_m at the beginning of the season, interval A, however, by the middle of the season $E_m > E_w$. Whether the differences in transpiration rates resulted in competition between the windbreak and the crop would depend upon the availability of soil water. Unfortunately a comprehensive record of soil water was not available, however soil water was most likely to be restricted to the upper soil horizons at the start of the season (Garba and Reynard, 1991). This suggested that at the time when E_w was much larger than E_m coincided with the time when water was restricted to the surface horizons, and competition severe. Transpiration from the millet exceeded that of the windbreak by the middle of the season, suggesting that competition from the windbreak on the crop was not larger than that exerted by an adjacent area of millet.

7.3 DISCUSSION

7.3.1 Competition

No yield reductions were measured near the windbreak in the trial 'Competition' in 1988, although yield reductions were measured in the trial 'Standard' (Chapter 2). Differences between these trials may have resulted from the late sowing of 'Competition' into a wet soil profile, whereas 'Standard' was dry seeded and germinated at the time of maximum competition (Figure 7.4). This hypothesis is supported by the large growth reduction near the windbreak in 1988 at the start of the season, decreasing towards the middle of the season (Figure 2.5). The zone of competition in 1989 was found to be within 1.5*h*, the 1988 sampling included only one point within this zone. The use of the improved short-duration variety C.I.V.T., which may be less sensitive to stress may have also contributed to the lack of noticeable decrease in yield close to the windbreak.

The use of Sadoré locale, more intensive sampling and a drier year in 1989 led to yield reductions up to 9 m (1.5*h*), from the windbreak in all trials. Yield reductions to 2.8*h* were found using the same windbreak in an irrigated dry season millet trial in Niger (ICRISAT, 1988). Competition for water would be expected to be larger under these circumstances because irrigation restricts active roots of both tree and

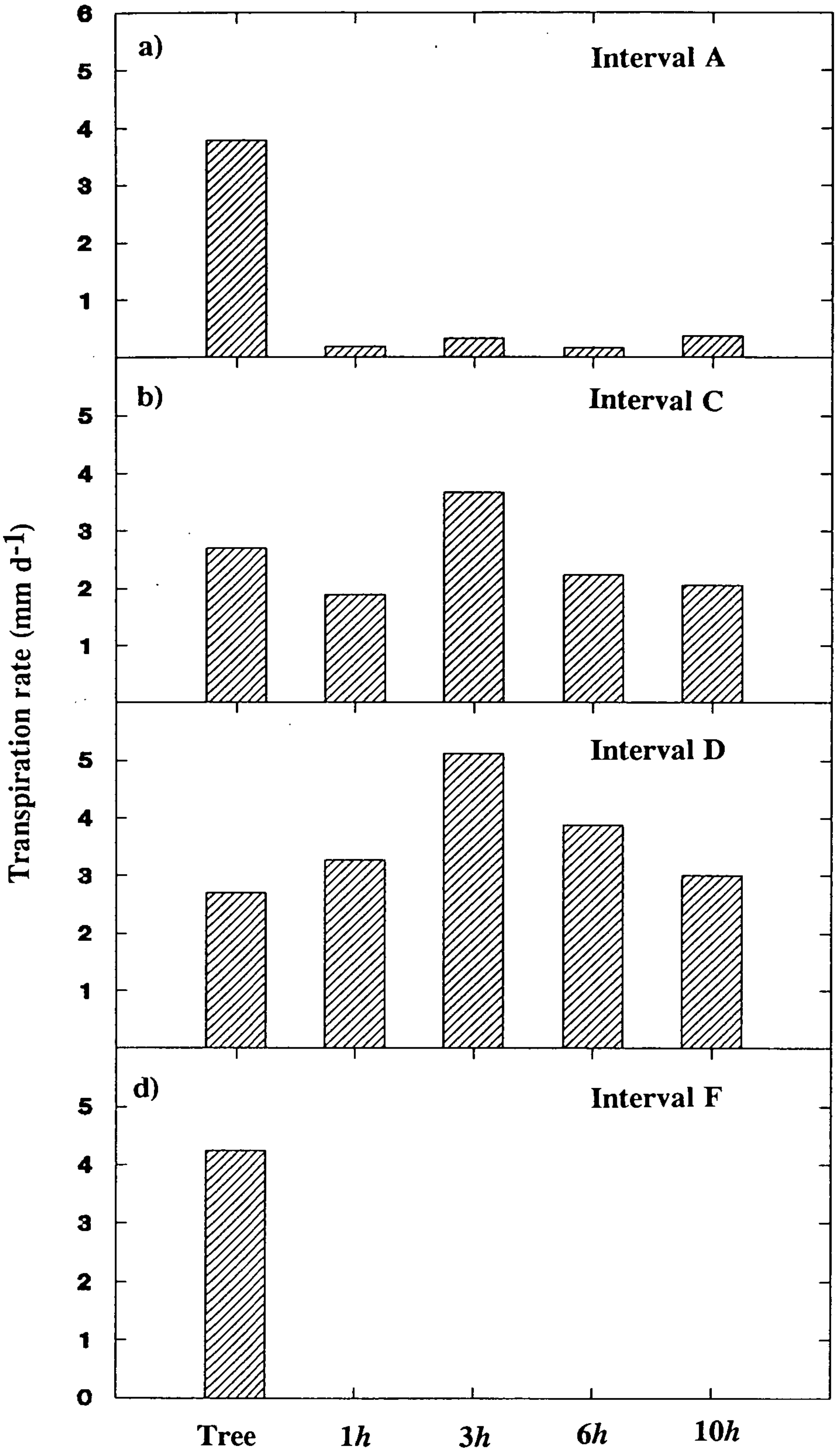


Figure 7.4 Daily transpiration rates of windbreak ('Tree') and millet crop at distances 1*h*, 3*h*, 6*h*, and 10*h*, from the windbreak, at a) Interval A, the start of the season, b) Interval C, the middle of the season, c) Interval D, the middle of the season and d) Interval F, the end of the season. Transpiration rates of the windbreak are based on the assumption that the water use by the windbreak occurs from a strip 7.0 m wide.

crop to the same zones. Whereas, in the rainy season, deeper drainage and wetting of both sides of the windbreak allows the windbreak to extract water from different soil horizons to those of the crop (Figure 7.3).

Yield reduction over 1.5*h* attributable to below-ground competition (Figure 7.2), was not large (ca. 15 %), and may have resulted from complementary rooting patterns of the two species. The maximum depth of the millet root zone lies between 75 - 145 cm (Payne *et al.*, 1990), and neem rooted well below 180 cm (Figure 7.3). Also high soil water deficits occurred only at the start of the season in 1989, under drier conditions yield reductions would be higher (ICRISAT, 1988).

Below-ground competition in the rainy season did not extend beyond the range of above-ground competition, approximately 1.5*h*. This corresponds to the pattern of rainy season water extraction for these windbreaks (ICRISAT, 1988) which shows a decrease in water extraction at a depth of 70 to 90 cm, at a distance of 1.5 to 2*h* from the windbreak. So while the profile was wet, water extraction at depth beyond this distance was small. Trees may not deplete all the water from the upper soil horizons before extracting water from deeper in the soil (Lovenstein *et al.*, 1991). So the deep rooting pattern of many semi-arid trees may reduce below-ground competition. Shankarnarayan *et al.* (1987), and Ong *et al.* (1991b) show that the deeper rooting *Prosopis cineraria* reduced crop yield less than the shallower rooting *Faidherbia albida*, however, one of the consequences reduced tree root ramification of the upper more fertile soil horizons was slower tree growth.

The extent of the above-ground competition corresponded to the incident PAR reduction caused by the windbreak. The decrease in millet biomass near the pruned windbreak of 13 % can be accounted for by the reduction in R_{par} available for photosynthesis, but the large decrease in grain yield (Figure 7.2a), cannot. Lower air temperatures near the windbreak (Section 5.3) may have delayed panicle development relative to the rest of the field, reducing the time available for grain filling, since all panicles on the sheltered field were harvested at the same time. The shortened duration of grain filling would have reduced grain size and panicle weight (ODA, 1987b), and thus reduced the harvest index, which is what was measured at 0.5*h* (Figure 7.1f). The immaturity of the panicles was noted near the windbreak in the field at final harvest.

Long and Persaud (1988) measured reductions of 20 % in both grain and stover yields behind a neem windbreak in the Maggia valley (0.5*h* to 2.0*h*, normalized to 2*h*) and these were attributed to competition for light. Larger reductions in grain yields than stover yields attributable to above-ground competition were observed in this trial. The Maggia valley system had closer spaced and denser windbreak than those at Sadoré, which may have reduced the importance of reduced leaf temperatures caused by accelerated flow under the canopy, and so reduced grain yields to a lesser extent. The denser canopy in the Maggia valley may have increased interception of R_{par} and thus increased competition for light, as compared to Sadoré.

Light quality changes beneath a tree crown, the ratio of red (655 - 665 nm) : far-red (725 - 735 nm) affects stem and leaf extension rates (Smith, 1981). Casal *et al.* (1985) found that changing the red: far red ratio reduced tillering and the proportion of mature buds that developed and increased the number of fertile tillers per plant in *Lolium multiflorum* Lam.. It is not known whether the same effects would be expected in millet, but Casal's data suggests that harvest index would not decrease in light with low red: far red ratios.

The relative importance of above- and below-ground competition is perhaps surprising, considering that many workers in the Great Plains consider below-ground competition to dominate (Kort, 1988; Lyles *et al.*, 1984; Greb and Black, 1961). The comparatively small yield reduction attributable to below-ground competition may be explained partly by the ability of millet to recover from early season stress, providing that there is sufficient water available later in the season, (Section 2.4.1; Corlett, 1989). Since Figure 7.4 and Figure 1.3 suggest that mid-season competition for water was low and rainfall was adequate in both trial years, below-ground competition was not as severe as expected.

7.3.2 Windbreak spacing

Calculations of crop yield based on different windbreak spacings were estimated, taking into account land taken out of production, reduction of yields near the windbreak and increase in yields as a result of shelter. It was assumed that the windbreaks occupied a 7 m wide strip (Section 6.3.4), competition was the same on both sides of the windbreak extending to 10 m (Table 7.2), and the sheltered crop response was the same as trial 'Standard' for 1989. Crop yields at windbreak spacings of 5*h*, 10*h*, 15*h* and 20*h* are shown in Table 7.3 relative to unsheltered yields.

Table 7.3 Percentage yield change compared to unsheltered yields for 1989, at different windbreak spacings taking into account land not planted.

Spacing	5*h*	10*h* (%)	15*h*	20*h*
Grain	71	102	102	90
Stover	98	123	129	117

Thus optimum spacing of windbreaks is between 10*h* to 15*h* yielding grain that compensate for the land taken out of production, and increasing stover production. The decrease in yield at closer spacing results from increasing windbreak- crop competition, whereas at wider spacings the yields decrease because of the reduction in shelter.

These calculations do not take into account the production of the tree crop and products or benefits derived from it. Since grain and stover yields in the windbreak system in this environment more than compensates for the land taken out of annual production, taking the productivity of the trees into account the productivity of the windbreak system as a whole exceeds that of an unsheltered millet field. In circumstances where root competition for water is less because of closer proximity of the water table to the surface, the net benefit of the windbreak system may be even larger (Long and Persaud, 1988).

The optimum spacing of windbreaks depends upon the environmental conditions and purpose of the windbreak. For field crop production spacings of 10*h* (Van Eimern *et al.*, 1964), 12*h* (Caborn, 1957), 11*h* to 14*h* (Woodruff, 1956), and 15*h* (Kort, 1988) have been generally recommended, and these spacings agree well with the results found here.

7.4 SUMMARY OF RESULTS

1) The extent of competition did not exceed a distance of 1.5*h* from the windbreak in either year, and was similar for above- and below-ground interactions.

2) Reduction of stover yields as a result of above-ground competition corresponded to the reduction of R_{par}, whereas decreases in grain yield were larger. Below-ground competition reduced grain and stover yield by the same amount.

3) Competition for water between tree and crop was most likely at the start of the season, becoming less important towards the middle of the season, because transpiration by the millet exceeded that of the windbreak, on a ground area basis.

4) Optimum windbreak spacing was between 10*h* to 15*h*. At narrower spacing competition would reduce crop yields, and at wider spacings the benefit of shelter would decrease. If windbreaks were planted at spacings of between 10*h* to 15*h*, the expected grain yield in 1989 would compensate for the loss of crop growing area and increase stover production by about 25 %.

CHAPTER EIGHT

CONCLUSIONS

8.1 INTRODUCTION

Expectations of the early eighties regarding the benefits of agroforestry were based on, the belief that the advantages were large and disadvantages small (Huxley, 1983; Steppler and Nair, 1987). The scientific information published over the last five years (Corlett, 1989; Lal, 1989; Ong *et al.*, 1991a) revealed negative competitive aspects of the system that may diminish the beneficial interactions, so reducing overall benefits to the farmer (Kerkoff, 1990; Kessler and Breman, 1991).

This realisation arose from measurement of the magnitude of tree-crop interactions on a whole-system basis rather than a single component level. Single component research is essential in establishing cause and effect under controlled conditions, however it is the balance of processes that determines crop growth and final yield in a farmer's field.

This project aimed to elucidate three areas of uncertainty (Section 1.5): (i) The effect of shelter on millet growth in the Sahel; (ii) the yield reduction from windbreak/crop competition; and (iii) the amount of water used by the windbreak. To address the first question the effect of windbreaks on microclimate needs to be established.

8.2 EFFECT OF WINDBREAKS ON MICROCLIMATE

Work on the aerodynamics of windbreaks, using inert fences or no crops in wind tunnels (Section 4.1), provides useful information on wind patterns for unchanging windbreak systems. In the field, windbreaks and crops grow, so the variables describing the system change constantly. For example, distance of minimum u behind a windbreak (x_{min}) moved from $6h$ at the start of the season to $3h$ by the middle and end of the season. In most windbreak systems it is assumed that x_{min} is constant, although movement of x_{min} has been reported with changes of windbreak porosity (ϕ) (Nageli, 1946; Konstantinov and Struzer, 1965; Raine and Stevenson, 1977). The response of u/u_0 to Θ also varied with porosity although not in a way expected with a uniform fence. At the beginning of the season the maximum average shelter over $15h$ (E_{15}) was found when $\Theta = 30^o$. By the middle of the season E_{15} was maximum when $\Theta = 90^o$. There was also an increase in wind variability at $6h$ and $10h$ towards the middle of the season in the wake zone (Figure 4.1), that runs from $8h$ to $15h$ (Figure 4.5).

The reason for the change in x_{min}, E_{15} and the increase in turbulence was the change in porosity of the lower half of the windbreak from $\phi = 0.6$ at the beginning of the season, to 0.1 by the middle of the season, caused by the growth of millet on the windward side of the windbreak blocking the gap below the windbreak. The change in average porosity was not as large (0.3 to 0.1), supporting the suggestion that the porosity of the lower half of the windbreak is more important in determining wind pattern than that of the upper half (Section 4.1.2). When ϕ was low the change of u/u_0 with Θ conformed to eq 4.3, agreeing with the results of Seigner (1975b) for slat fences (Section 4.2.2.).

In general the results found here agree with data from wind tunnel and slat fences (Heisler and Dewalle, 1988), as long as the change in effective porosity of the windbreak over the season with wind direction and at high incident wind speeds is taken into account. So, if the functional relationship expressed in eq 4.1 was to be used, different parameters would need to be derived for different times in the season.

The relationships between u and g_a measured with heated leaf replicas were similar to those calculated from laminar flow theory for $u < 2.5$ m s^{-1} and did not seem to vary with the turbulent intensity measured with cup anemometers above the crop. This seems initially to be surprising. However, if turbulence at the scale of the leaf was similar at all distances from the windbreak the relationship would be expected to remain the same. Turbulent intensity did affect transfer from the surface of the crop to the atmosphere (Figures 5.8 and 5.10).

8.3 EFFECT OF MICROCLIMATE ON CROP

An evaluation of shelter requires knowledge of individual processes controlling plant growth at each point in the season, rather than taking a seasonal average. In Niger, at the start of the season, the system was dry so temperatures of soil, leaf and air were high and became even higher in shelter because H was the major energy flux. These high temperatures especially in the soil, probably exceeded T^{g}_{opt} and T^{l}_{opt}. Under such conditions, and coupled with water stress, the shelter at $6h$ was a disadvantage, delaying seedling emergence and development of the millet. This effect persisted throughout the season, delaying stem elongation and panicle emergence, despite the improved growth conditions at $6h$ later in the season.

By the middle of the season x_{min} was at $3h$, the system had become wetter (increased transpiring leaf area and rain), and average temperatures had generally dropped below T^{l}_{opt}. So the increase of temperature in shelter increased leaf expansion, enabling more light interception and growth (Chapter 5).

Large leaf areas and low wind speeds in shelter allowed water vapour to accumulate within the crop canopy increasing e_{a}. The effect on D_{a} was small because of the parallel rise in temperature, but there was a decrease in D_{surf}. D_{surf} is negatively correlated to g_{s} (Grantz and Meinzer, 1991; Turner, 1991), and the decrease in D_{surf} was probably the main cause of the increase in g_{s} measured in shelter during the middle of the season. The decrease in D_{surf} and increase in g_{s} was associated with a rise in the solar radiation conversion ratio, ie. an increase in the efficiency of carbon fixation per unit energy absorbed.

However, shelter may not always have these effects. Under dry conditions shelter may increase D_{surf} (see Section 5.2.5.5.) and decrease g_{s} (Figure 5.15a). Changes in g_{s} may not always affect $\hat{e}$ in this way; in situations where the photosynthetic capacity or the conductance of carbon dioxide across the cell membrane to the chloroplast (mesophyll conductance) is low, changes in g_{s} may have a little or no effect on photosynthesis. Values for mesophyll conductances are similar in size to the other conductances for C3 plants but are somewhat higher in C4 plants (Lawlor, 1987; Von Caemmerer and Evans, 1991). Under high quantum flux densities total conductance in C4 plants is highly dependent on g_s (Weyers and Meidner, 1990)

The importance of faster canopy expansion in shelter may be reduced by shorter canopy duration, reducing the increase in final harvest yield in shelter (Section 2.4.2.). In times of end-season drought, earlier maturation may increase final yields, but in 1988 (a wet year) grain yields were reduced relative to the unsheltered site because early maturation increased bird and insect damage, and provided no advantage when compared to the slower development and longer duration of the canopy on the unsheltered field. Increased fungal infestation, because of the warmer and more humid microclimate, may have also reduced yields, as was observed by Shah (1961) and Skidmore *et al.* (1974).

In 1989 grain yields were not substantially increased in shelter despite the increase in biomass and thus led to a consistently lower harvest index. The smaller grains, lower grain weight per panicle and similar grain yields found in shelter as compared to unsheltered sites, suggested that there was little advantage for grain yields in shelter. This probably resulted from a reduction of the duration of grain filling because of the higher temperatures found in shelter (Ong and Monteith, 1985).

Growth of cereals (Stoeckler, 1962; Kort, 1988), tea (Carr, 1985) and cotton (Barker *et al.*, 1989) respond more to shelter at low ambient temperatures than at high temperatures. This may be because the low temperatures are further away from the optimum temperature for growth, so the increase in temperature has a larger effect on the crop than when the ambient temperature is near the optimum. Generally $T^l{}_{\mathrm{opt}} > T^s{}_{\mathrm{opt}}$ explaining why harvest index of maize (Bates, 1911), millet (Long and Persaud, 1988), and wheat (Vora *et al.*, 1982), decrease in shelter. It may also explain why fodder crops (vegetative production) are thought to be more responsive to shelter more than cereals (seed/grain production).

However, harvest index does not always decrease in shelter. In pod-forming crops, eg. soybeans (Ogbuehi and Brandle, 1982) and mustard (Vora *et al.*, 1982), harvest index increases in shelter. It was observed in soybean that, although pod formation started earlier in shelter, maturity was reached at the same time as in the unsheltered crop, the duration of pod filling increasing. There may be other factors, such as the positive effect of reduction of night-time temperatures on pod productivity (Konsens *et al.*, 1991) that also may be important.

Stomatal conductance is higher in shelter in wet conditions (Rosenberg, 1966; Miller *et al.*, 1973; Frank *et al.*, 1974), whereas, as drought ensues g_s decreases in shelter (Frank *et al.*, 1974; Frank *et al.*, 1977; Radke and Hagstrom, 1973). This would suggest that crops in semi-arid environments may not benefit from shelter as much as those in wetter climates, but data in Table 2.1 indicate otherwise. The discrepancy may be accounted for by the use of irrigation in two of the experiments: yields will almost always benefit from shelter when irrigation is applied, because of the reduction of evaporation of irrigation water (Section 5.1.6), and the importance of advection in these situations.

In the dryland experiments information was not given as to the leaf area of the crop or whether the plants were stressed during the rainy season since, in the semi-arid tropics, water is often not the primary factor limiting production (Kessler and Breman, 1991; Payne *et al.*, 1991). Most trial data, including the results of the trials reported here, show an increase in yield behind windbreaks, which suggests that, conditions under which a yield decrease would be expected are rarely found. However, comparing the millet yield data for two years from Reddi *et al.* (1981; Table 2.1), it is possible to see that the benefit of shelter was reduced in the drier of the two years.

Yield increases resulting from the conservation of water behind windbreaks, resulting in less soil water depletion and less drought stress, were not found here. Although Penman potential evaporation decreases in shelter, crop transpiration may often increase. This increase may result from an increase in transpiration per unit leaf area as well as an increase in leaf area. Transpiration per unit leaf area may decrease in shelter under strong advective conditions for well-watered crops (Miller *et al.*, 1973). However, under dryland conditions, transpiration is generally expected to increase (Section 5.1.7), because the combined effects of the increases in g_s and T_l in shelter affect transpiration more than the decrease in g_a and increase in e_a. This suggests that reduced water use may not generally be the cause of the yield increase in shelter, although the water use efficiency of a sheltered crop may increase when D_{surf} decreases (Section 5.2.6).

8.4 EFFECT OF TREE ON CROP

Competition between windbreak and crop varies with size of the windbreak, and the relative proportions of above- and below-ground interference. Above-ground competition is mainly attributable to reduction in PAR incident upon the crop. However, both light quality and flux density as well as the reduction of air and leaf temperature should be considered. Although the reduction of biomass may be fully explained by the reduction in PAR, the larger reduction in grain yield suggests that there may be other effects, such as low temperature delaying plant development and reducing duration of grain filling. Low temperatures at 1*h* resulted from increased wind speeds caused by preferential flow of air under the crop (Section 4.2.1), rather than from shading (Section 5.2.2), and so would be less likely to occur where the windbreak was of uniform porosity.

The extent of below-ground competition did not exceed that above-ground (1.5*h*), as found by Kort (1988), and Lyles *et al.*, (1984). However, these results are for relatively wet years. In the dry season, competition by the same windbreaks has been noted to extend to 2.8*h* (ICRISAT, 1988), and in dry areas yield reductions have been noted to extend beyond 4.5*h* (Greb and Black, 1961; Prajapati *et al.*, 1971). In general, however, competition for light does not extend beyond 1.5*h*, with below-ground competition reducing yields to a similar extent except under dry conditions.

8.5 EFFECT OF SYSTEM ON ENVIRONMENT

One major concern in establishing large areas of windbreaks is the effect on the water balance of the catchment, a problem that is rarely assessed by project planners. Windbreak transpiration was only measured up to the beginning of April, so for the purpose of annual transpiration calculations it was assumed that the same transpiration rate was maintained between April and the start of the new rains. This assumption is reasonable since the change of transpiration rate between periods 3 and 4 was small (3 %). Weighting the values of daily windbreak transpiration

(Table 6.6) by the number of days that each time period is represented, total transpiration, assuming extraction from a 7 m wide strip, over the year was 674 mm a^{-1} in 1988 and 1021 mm a^{-1} in 1989. This may be compared to calculated annual Penman potential evaporation rates of 2485 mm a^{-1} (Sivakumar, 1987). Eastham *et al.* (1988) found that a stand of 3-year-old *Eucalyptus grandis*, spaced 2.8 m apart transpired a similar amount of 1083 mm a^{-1}.

Taking crop transpiration from Table 5.11, and weighting the values to correspond to the area that they represent, the transpiration for the field can be calculated. The average daily transpiration for each interval was multiplied by the number of days in intervals A to D, which accounted for the first 80 days of the cropping season. Transpiration after this date was less certain because of uncertainties in the estimation of green leaf area. An average daily transpiration rate for the field of 2.1 mm d^{-1} was estimated for the final 30 days, (average of intervals B to D), not dissimilar to that measured by Wallace *et al.* (1989) for the end of the cropping season. This calculation gave an estimated field water use of 175 mm for the season, falling within the range of values for the Sahel of between 120 mm (Azam-Ali, 1983) and 330 mm (including soil evaporation; Kassam and Kowal, 1975). ODA (1987a) estimated that on average millet would transpire around 200 mm over a cropping season.

Table 8.1 presents the volume transpired from a 1 hectare plot, with a double row 6-year-old neem windbreak spaced 100 m apart, intercropped with millet.

Table 8.1 Volume of water transpired by a neem windbreak system, with windbreaks spaced 100 m apart. Based on data from 1989-1990.

	Windbreak	Millet	Total	Sole millet
Length (m)	100	100	100	100
Width (m)	7	93	100	100
Area (m^2)	700	9 300	10 000	10 000
Water use	(m^3 $0.7ha^{-1}$)	(m^3 $0.93ha^{-1}$)		(m^3 ha^{-1})
Cropping season	254	1 628	1 881	1 750
Dry season	461	0	461	0
Total	715	1 628	2 342	1 750

The calculation above are based on a 110 day cropping season and assumes no water is lost from bare soil in the dry season. From Table 8.1 it is possible to calculate that a 6-year-old double row neem windbreak spaced 100 m apart intercropped with millet uses approximately 60 mm more water per year than a millet crop alone. Taking the average rainfall of the area as 550 mm, this constitutes about 11 % of the annual rains.

8.6 RECOMMENDATIONS FOR WINDBREAKS IN THE SAHEL.

This project has outlined the factors that need to be considered when designing and planning windbreaks for the Sahel, or any other semi-arid environment. Below are some of the recommendations:

1) Yield increases are not substantial behind windbreaks in the Sahel, although they do compensate for land taken out of production. The optimum spacing was between 10*h* - 15*h*. The beneficial effects of shelter may decrease in dry years and in areas of very low rainfall, unless advection is

important (ie. irrigated area in the dry season, or a cropped area during the Harmattan).

2) Windbreaks will increase average day-time temperatures, but the effect on growth depends upon the crop and stage of development. Crop varieties or cultivars that respond positively to increases in day-time temperatures, rather than those that are easily temperature stressed should be selected.

3) Root pruning does not make a major difference to yield if crops are grown during the rainy season. Pruning the canopy reduces both above- and below-ground competition, so the development of a management system that allows the harvest of leaves as a product would benefit the system.

4) The relative importance of windbreak transpiration depends upon the overall water balance of the area. In areas where the water table is not accessible to the tree roots, windbreak size is limited by water availability in the dry season. In these situations it is probably best to reduce the size of the windbreak and have them spaced closer together in distance terms (retaining the $10h$ to $15h$ spacing). This is also better from the perspective of soil erosion although it means planting more trees.

5) The primary benefits of windbreaks for the farmer are the tree products produced and the prevention of soil erosion. The use of a single tree species that allows a gap to develop beneath the windbreak is inefficient in producing effective shelter and in providing a variety of products. A good design of windbreaks for farmers in the Sahel may consist of three rows of trees;

(i) a leguminous tree to provide leaves and pods for various uses on the windward side of the windbreak;
(ii) a fast-growing (probably exotic) species for the middle row to give the windbreak a rapid height increment and provide construction poles; and
(iii) a fruit tree on the leeward side.

This should provide a good variety of products and create a windbreak with a uniform porosity and rapid height increment.

In order to make more accurate prediction of when shelter has the largest benefit more information is needed on the following.

1) Under what conditions D_{surf} increases and decreases. Although this is complex it could be achieved with the help of a model based on the leaf energy balance as used in Chapter 1. Such a model should include feedbacks to account for effects of changes in D_{surf} on g_s and the ability to scale from a leaf to a sparse crop.

2) What would happen with windbreaks planted in areas of high water tables. If the tree had free access to water, transpiration would not decrease as rapidly into the dry season as was observed here, where 11 % more of the annual rainfall was used by the windbreak system than a simple millet cropping system. In areas of high water tables the rates could easily be double this. Since windbreaks have been considered successful in areas of high water tables they are widely recommended without any idea of their effect on the overall water balance of the area. Measurements need to be made to establish the significance of windbreak water use under these conditions.

3) The influence of advection has not been addressed by this project, but may be the dominant factor in irrigated agriculture in arid zones. Measurements as to the importance of advection needs to be carried out.

Although crop growth behind windbreak systems involves a series of complex interactions, if the processes controlling those interactions are considered the reasons for the diversity of plant responses can be unravelled, and recommendations can be made on a sound scientific basis rather than empirical extrapolation.

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APPENDIX I

SYMBOLS AND ABBREVIATIONS

a	intercept for regression equations
a_t	coefficient of thermal expansion
A_t	total surface area
A_p	plan surface area
A_l	leaf surface area
A_{sw}	sapwood basal area
A_{st}	stem basal area
A_{sam}	leaf area of sample
b	slope for regression equations
C_p	specific heat capacity of air at constant pressure
C_b	specific heat capacity of brass
D_h	diffusion coefficient of heat in air
D_v	diffusion coefficient of vapour in air
D_a	saturated vapour pressure deficit of the air
D_{surf}	saturated vapour pressure deficit at the surface of the leaf
D_o	saturated vapour pressure deficit at a reference height
d	characteristic dimension of an object
d	displacement height
E	flux of water vapour per unit area
E_w	tranpiration of the windbreak
E_m	transpiration of the millet crop
E_{15}	average effectiveness of the windbreak over a distance of 15h from the windbreak
e_a	vapour pressure of air
e_o	vapour pressure at a refernce height
e_l	vapour pressure in the sub-stomatal cavity
e_{surf}	vapour pressure at the surface of the leaf
$e^*(T)$	saturated vapour pressure at temperature T.
$\hat{e}$	solar radiation conversion coefficient

F	F statistic
G_s	ground heat flux per unit area
G_p	conduction of heat to and from the plant
g	acceleration due to gravity
g_s	stomatal conductance
g_{smax}	maximum stomatal conductance
g_a^h	leaf boundary layer conductance to heat transfer.
g_a^v	leaf boundary layer conductance to water vapour
g_c	leaf cuticular conductance
g_{leaf}	total leaf conductance for water vapour
H	sensible heat flux per unit area
h	height of windbreak
h_c	crop height
i	electrical current
K	crop extinction coefficient
k	Von Karmans constant
L_a	longwave radiation absorbed
L_e	longwave radiation emmitted
L_u	upward longwave radiation
L_d	downward longwave radiation
L	leaf area index
L	Monin-Obukov stability length
m	mass
n	number of replicates
N_{hec}	number of hills per hecatare
N_{sam}	number of hills in a sample
P	atmospheric pressure
P_e	electrical power
P_s	energy flux to photosynthesis
p	number of parameters of fitted curve
Q	quantum flux density
Q_{sat}	quantum flux density at which g_{smax} is attained
r	electrical resistance
R_n	net radiation

$(R_n)_a$	actual net radiation
$(R_n)_d$	net radiation measured with a double domed net radiometer
$R_n{}^a$	net radiation absorbed
R_{par}	photosynthetically active radiation
s	rate of change of saturation vapour pressure with temperature
s^2	varience of sample
S	heat storage
S_t	total solar radiation
S_n	net solar radiation
S_i	intercepted solar radiation
t	number of treatments
t_s	transmissivity of solar radiation
t_{par}	transmissivity of PAR
T_a	air temperature
T_s	surface temperature
T_l	leaf temperature
T_o	air temperature at a reference height
$T^g{}_{opt}$	optimum temperature for germination
$T^l{}_{opt}$	optimum temperature for leaf growth
$T^s{}_{opt}$	optimum temperature for seed or grain growth
u	horizontal wind velocity
u_o	incident horizontal wind velocity
u_*	friction velocity
v	kinematic viscosity
w	vertical wind velocity
x	distance from windbreak
x_{min}	distance from the windbreak when u/u_o is minimum
Y_p	yield of millet adjacent to a root pruned windbreak
Y_u	yield of millet adjacent to an unpruned windbreak
z	height
z_o	roughness length

Dimensionless groups

Nu	Nusselt number

Re	Reynolds number
Gr	Grashof number
Ri	Richardson number

Greek alphabet

α	solar reflectivity
α_m	solar reflectivity of millet leaves
α_s	solar reflectivity of soil
γ	psychrometric constant
ϵ	emmisivity
ε	s / γ
λ	latent heat of vapourisation
ρ_a	density of air
σ	Stefan-Boltzmann constant
σ_u	standard deviation of wind speed
Ω	decoupling coefficient.
ϕ	porosity of windbreak
Θ	angle of incidence of wind from orientation of windbreak
λE_{imp}	imposed transpiration
λE_{eq}	equilibrium transpiration

Abbreviations

CAN	calcium ammonium nitrate
DAS	days after sowing
d.f.	degrees of freedom
'E'	eastern side of the windbreak
M.S.	mean square
NWV	normalized wind variabilities
PM	Penman-Monteith
s.e.	standard error of the mean
SLA	specific leaf area
S.S.	sums of squares
WV	wind variability
'W'	western side of the windbreak

APPENDIX II

SEQUENTIAL AND FINAL HARVEST DATA FOR 1988 AND 1989

Sequential harvest data for 1988 and 1989 is presented in the following tables standard errors were calculated from the poolsed variance of all treatment distances. Sig from cont indicates the distances that were significantly different from the unsheltered control at the 5 % level calculated with the Tukey test. Sig from 15 m (or 18 m for 1989 data) indicates the distances that were significantly different from 3*h*. The coding for this was 1 = 1*h*, 2 = 3*h*, 3 = 6*h*, 4 = 10*h*, 5 = 20*h*, and c = unsheltered control.

SEQUENTIAL HARVEST DATA 1988

TABLE II.1

DATE - 8/7 DAYS AFTER RAINS - 27

DISTANCE FROM WINDBREAK	DRY WEIGHTS (t ha^{-1}) leaf	stem	panicle	total
5 m	0.018	0.005	0.000	0.023
15 m	0.068	0.021	0.000	0.089
50 m	0.031	0.010	0.000	0.041
CONTROL	0.023	0.009	0.000	0.032
mean	0.035	0.011	-	0.046
s.e. (n = 24)	0.006	0.001	-	0.006
sig from cont	2	none	-	2
sig from 15m	1,4,c	1	-	1,c

DISTANCE FROM WINDBREAK	Leaf Area Index	SLA cm^2 g^{-1}	Plant Height cm	Tiller-panicle Number
5 m	0.046	242.48	20.4	3.3 - 0
15 m	0.164	237.65	39.9	5.0 - 0
50 m	0.070	222.37	29.8	3.7 - 0
CONTROL	0.056	243.40	25.0	3.8 - 0
mean	0.084	236.5	28.8	4.0 - 0
s.e. (n = 24)	0.013	4.4	1.5	0.2 - 0
sig from cont	2	none	2	none
sig from 15m	1,c	none	1,c	1

TABLE II.2

DATE - 27/7 DAYS AFTER RAINS - 46

DISTANCE FROM WINDBREAK	leaf	DRY WEIGHTS (t ha^{-1}) stem	panicle	total
5 m	0.390	0.127	0.000	0.518
15 m	0.825	0.300	0.000	1.125
50 m	0.630	0.229	0.000	0.859
CONTROL	0.734	0.260	0.000	0.994
mean	0.645	0.229	-	0.874
s.e. (*n* = 24)	0.044	0.018	-	0.058
sig from cont	none	none	-	1
sig from 15m	1	1	-	1

DISTANCE FROM WINDBREAK	Leaf Area Index	SLA cm^2 g^{-1}	Plant Height cm	Tiller-panicle Number
5 m	1.065	271.10	60.6	9.0 - 0
15 m	1.968	240.93	64.0	12.0 - 0
30 m	1.453	230.60	49.4	10.0 - 0
CONTROL	1.681	227.92	57.1	10.8 - 0
mean	1.542	242.60	57.8	10.4 - 0
s.e. (*n* = 24)	0.111	4.97	1.6	0.3 - 0
sig from cont	none	1	none	none
sig from 15m	1	none	4	1

TABLE II.3

DATE - 11/8 DAYS AFTER RAINS - 61

DISTANCE FROM WINDBREAK	leaf	DRY WEIGHTS (t ha^{-1}) stem	panicle	total
5 m	1.532	2.656	0.000	4.188
15 m	2.041	2.777	0.026	4.843
50 m	1.926	2.003	0.022	3.951
CONTROL	1.722	3.093	0.007	4.821
mean	1.805	2.632	0.014	4.451
s.e. (*n* = 24)	0.117	0.308	0.001	0.388
sig from cont	none	none	-	none
sig from 15m	none	none	-	none

DISTANCE FROM WINDBREAK	Leaf Area Index	SLA cm^2 g^{-1}	Plant Height cm	Tiller-panicle Number
5 m	3.031	198.10	173.5	4.3 - 0.1
15 m	3.481	171.45	216.9	3.7 - 0.3
50 m	3.319	172.63	173.7	2.4 - 0.2
CONTROL	2.604	152.95	180.5	7.1 - 0.3
mean	3.109	173.8	186.1	4.4 - 0.2
s.e. (n = 24)	0.190	3.7	7.5	0.2 - 0.06
sig from cont	none	1	none	1,2,4 - none
sig from 15m	none	none	none	c - none

TABLE II.4
DATE - 29/8 DAYS AFTER RAINS - 79

DISTANCE FROM WINDBREAK		DRY WEIGHTS (t ha^{-1})		
	leaf	stem	panicle	total
5 m	1.311	3.836	0.687	5.834
15 m	1.447	5.302	1.067	7.817
50 m	1.477	3.860	0.983	6.320
CONTROL	1.807	4.962	0.985	7.754
mean	1.510	4.490	0.931	6.931
s.e. (n = 24)	0.081	0.270	0.053	0.362
sig from cont	none	none	none	none
sig from 15m	none	none	none	none

DISTANCE FROM WINDBREAK	Leaf Area Index	SLA cm^2 g^{-1}	Plant Height cm	Tiller-panicle Number
5 m	1.692	129.30	301.6	5.1 - 2.8
15 m	1.915	129.22	312.6	5.7 - 3.6
50 m	2.167	146.22	283.2	5.6 - 3.3
CONTROL	2.455	133.10	305.1	7.0 - 3.6
mean	2.057	134.50	300.6	5.8 - 3.3
s.e. (n = 24)	0.137	4.02	4.8	0.2 - 0.1
sig from cont	none	none	none	1,2,4 - none
sig from 15m	none	none	none	c - none

TABLE II.5
DATE - 26/9 DAYS AFTER RAINS - 107

DISTANCE FROM WINDBREAK	DRY WEIGHTS ($t\ ha^{-1}$) leaf	stem	panicle	total
5 m	2.172	3.143	1.945	7.260
15 m	2.840	4.095	2.643	9.578
30 m	2.510	3.879	2.230	8.619
CONTROL	2.337	4.385	3.141	9.862
mean	2.465	3.875	2.490	8.830
s.e. (*n* = 24)	0.078	0.207	0.114	0.351
sig from cont	none	none	1	none
sig from 15m	1	none	none	none

DISTANCE FROM WINDBREAK	Leaf Area Index	SLA $cm^2\ g^{-1}$	Plant Height cm	Tiller-panicle Number
5 m	0.034	64.3	277.9	3.9 - 2.9
15 m	0.031	64.3	319.9	3.5 - 3.1
30 m	0.033	64.3	278.0	3.2 - 3.4
CONTROL	0.024	64.3	297.0	3.8 - 4.6
mean	0.030	64.3	293.2	3.6 - 3.5
s.e. (*n* = 24)	0.003	-	4.3	0.1 - 0.1
sig from cont	none	none	none	none - 1,2
sig from 15m	none	none	1	none - none

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TABLE II.6
DATE - 10/8 DAYS AFTER RAINS - 36

DISTANCE FROM WINDBREAK	DRY WEIGHTS ($t\ ha^{-1}$) leaf	stem	panicle	total
6 m	0.050	0.020	0.000	0.069
18 m	0.081	0.031	0.000	0.112
36 m	0.047	0.020	0.000	0.067
60 m	0.100	0.040	0.000	0.139
120 m	0.037	0.016	0.000	0.053
CONTROL	0.017	0.009	0.000	0.026
mean	0.055	0.023	-	0.078
s.e. (*n* = 36)	0.005	0.002	-	0.007
sig from cont	2,4	2,4	-	2,4
sig from 18 m	c	c	-	c

DISTANCE FROM WINDBREAK	Leaf Area Index	SLA $cm^2 g^{-1}$	Plant Height cm
6 m	0.105	212.93	29.1
18 m	0.171	210.05	33.6
36 m	0.091	196.08	28.7
60 m	0.200	200.99	36.0
120 m	0.082	211.88	23.8
CONTROL	0.052	333.72	25.7
mean	0.117	227.61	29.4
s.e. (*n* = 36)	0.011	7.38	0.9
sig from cont	2,4	2,4	4
sig from 18 m	c	c	5

TABLE II.7

DATE - 17/8 DAYS AFTER RAINS - 43

DISTANCE FROM WINDBREAK	DRY WEIGHTS (t ha^{-1}) leaf	stem	panicle	total
6 m	0.076	0.039	0.000	0.115
18 m	0.158	0.105	0.000	0.263
36 m	0.078	0.036	0.000	0.115
60 m	0.136	0.078	0.000	0.214
120 m	0.098	0.046	0.000	0.145
CONTROL	0.090	0.038	0.000	0.128
mean	0.106	0.057	-	0.158
s.e. (*n* = 30)	0.012	0.008	-	0.018
sig from cont	none	none	-	none
sig from 18 m	none	none	-	none

DISTANCE FROM WINDBREAK	Leaf Area Index	SLA $cm^2 g^{-1}$	Plant Height cm
6 m	0.197	260.32	38.2
18 m	0.375	241.30	43.5
36 m	0.182	238.14	38.7
60 m	0.291	218.83	41.9
120 m	0.226	232.00	37.7
CONTROL	0.221	242.44	28.8
mean	0.249	238.84	38.1
s.e. (*n* = 30)	0.026	4.63	1.3
sig from cont	none	none	2
sig from 18 m	none	none	c

TABLE II.8

DATE - 25/8 DAYS AFTER RAINS - 50

DISTANCE FROM WINDBREAK	DRY WEIGHTS (t ha^{-1}) leaf	stem	panicle	total
6 m	0.268	0.134	0.000	0.402
18 m	0.372	0.294	0.000	0.666
36 m	0.229	0.140	0.000	0.369
60 m	0.245	0.137	0.000	0.382
120 m	0.197	0.141	0.000	0.337
CONTROL	0.131	0.057	0.000	0.188
mean	0.240	0.151	-	0.391
s.e. (*n* = 30)	0.024	0.019	-	0.042
sig from cont	none	2	-	2
sig from 18 m	none	c	-	c

DISTANCE FROM WINDBREAK	Leaf Area Index	SLA cm^2 g^{-1}	Plant Height cm
6 m	0.607	227.72	45.8
18 m	0.715	195.62	47.3
36 m	0.395	179.10	37.7
60 m	0.501	196.83	38.6
120 m	0.357	183.51	40.2
CONTROL	0.182	146.06	26.4
mean	0.459	188.14	39.3
s.e. (*n* = 30)	0.049	5.77	2.2
sig from cont	2	1	none
sig from 18 m	c	none	none

TABLE II.9

DATE - 30/8 DAYS AFTER RAINS - 56

DISTANCE FROM WINDBREAK	DRY WEIGHTS (t ha^{-1}) leaf	stem	panicle	total
6 m	0.423	0.321	0.000	0.745
18 m	0.853	0.697	0.000	1.550
36 m	0.516	0.445	0.000	0.961
60 m	0.547	0.804	0.000	1.351
120 m	0.292	0.277	0.000	0.569
CONTROL	0.188	0.096	0.000	0.284
mean	0.470	0.440	-	0.910
s.e. (*n* = 30)	0.037	0.042	-	0.069
sig from cont	2	2,4	-	2,4
sig from 18 m	1,5,c	c	-	1,5,c

DISTANCE FROM WINDBREAK	Leaf Area Index	SLA cm^2 g^{-1}	Plant Height cm
6 m	0.756	175.08	72.4
18 m	1.489	176.40	98.0
36 m	0.851	164.92	78.1
60 m	0.883	160.78	93.7
120 m	0.483	167.41	64.0
CONTROL	0.313	165.74	51.1
mean	0.796	168.39	76.2
s.e. (*n* = 30)	0.065	2.08	3.2
sig from cont	2	none	2,4
sig from 18 m	1,5,c	none	c

TABLE II.10

DATE - 7/9 DAYS AFTER RAINS - 62

DISTANCE FROM		DRY WEIGHTS (t ha^{-1})		
WINDBREAK	leaf	stem	panicle	total
6 m	1.009	0.979	0.037	2.025
18 m	1.396	2.383	0.136	3.915
36 m	1.102	0.888	0.040	2.029
60 m	0.667	0.659	0.087	1.413
120 m	0.642	0.527	0.006	1.175
CONTROL	0.611	0.481	0.015	1.107
mean	0.904	0.986	0.053	1.144
s.e. (*n* = 30)	0.059	0.130	0.013	0.179
sig from cont	2	2	none	2
sig from 18 m	4,5,c	1,3,4,5,c	none	4,5,c

DISTANCE FROM WINDBREAK	Leaf Area Index	SLA cm^2 g^{-1}	Plant Height cm
6 m	1.978	197.13	136.6
18 m	2.494	179.47	169.1
36 m	1.882	169.74	126.5
60 m	1.110	160.26	100.9
120 m	1.088	171.95	106.8
CONTROL	1.097	180.01	67.1
mean	1.608	176.43	117.8
s.e. (*n* = 30)	0.012	3.18	5.6
sig from cont	2	none	1,2
sig from 18 m	4,5,c	none	4,5,c

TABLE II.11

DATE - 14/9 DAYS AFTER RAINS - 71

DISTANCE FROM WINDBREAK	leaf	DRY WEIGHTS (t ha^{-1}) stem	panicle	total
6 m	1.019	1.582	0.276	2.878
18 m	1.430	2.637	0.409	4.476
36 m	1.165	1.707	0.264	3.136
60 m	1.047	1.433	0.155	2.635
120 m	0.597	0.734	0.087	1.418
CONTROL	1.114	1.031	0.119	2.264
mean	1.062	1.521	0.219	2.801
s.e. (n = 30)	0.048	0.112	0.025	0.032
sig from cont	none	2	2	2
sig from 18 m	5	4,5,c	5,c	5,c

DISTANCE FROM WINDBREAK	Leaf Area Index	SLA cm^2 g^{-1}	Plant Height cm
6 m	1.803	177.43	186.5
18 m	2.361	167.17	209.7
36 m	2.047	175.13	167.9
60 m	1.703	162.06	168.4
120 m	0.968	162.98	141.6
CONTROL	1.819	161.18	99.0
mean	1.783	167.66	162.2
s.e. (n = 30)	0.083	2.54	5.5
sig from cont	none	none	1,2,3,4
sig from 18 m	none	5	5,c

TABLE II.12

DATE - 28/9 DAYS AFTER RAINS - 85

DISTANCE FROM WINDBREAK	leaf	DRY WEIGHTS (t ha^{-1}) stem	panicle	total
6 m	0.909	2.288	1.132	4.329
18 m	1.315	4.020	1.640	6.975
36 m	1.105	3.514	1.521	6.139
60 m	1.032	3.340	1.560	5.932
120 m	0.764	2.618	0.856	4.238
CONTROL	0.771	2.736	0.854	4.361
mean	0.983	3.086	1.260	5.329
s.e. (n = 30)	0.066	0.218	0.091	0.363
sig from cont	none	none	none	none
sig from 18 m	none	none	none	none

DISTANCE FROM WINDBREAK	Leaf Area Index	SLA cm^2 g^{-1}	Plant Height cm
6 m	1.411	155.12	209.1
18 m	1.765	134.31	236.6
36 m	1.555	140.35	237.7
60 m	1.334	128.63	235.9
120 m	1.087	141.00	206.7
CONTROL	1.115	143.79	158.4
mean	1.378	140.53	214.1
s.e. (*n* = 30)	0.096	3.37	6.9
sig from cont	none	none	2,3,4
sig from 18 m	none	none	c

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TABLE II.13 'STANDARD'

DISTANCE FROM		DRY WEIGHTS (t ha^{-1})		
WINDBREAK	grain	stover	panicle	total
5 m	0.404	4.373	0.903	5.275
15 m	0.895	6.705	1.760	8.465
30 m	0.722	5.398	1.513	6.912
50 m	0.767	5.178	1.509	6.687
CONTROL	1.363	6.242	2.279	8.520
mean	0.830	5.579	1.593	7.172
s.e. (*n* = 30)	0.052	0.198	0.075	0.261
sig from cont	1,3,4	1	1,3,4	1
sig from 15m	1	1	1	1

DISTANCE FROM WINDBREAK	1000 grain Weight (g)	Harvest Index	No. full panicles (10^3)	Weight of panicle (g)
5 m	8.27	0.075	40.19	9.7
15 m	8.10	0.105	54.80	16.2
30 m	8.73	0.103	41.40	17.3
50 m	9.08	0.112	45.25	16.6
CONTROL	9.72	0.158	54.90	24.6
mean	8.780	0.111	47.31	16.9
s.e. (*n* = 30)	0.109	0.006	1.55	0.7
sig from cont	1,2,3	1,2,3,4	1	1,2,3,4
sig from 15m	c	c	1	1,c

TABLE II.14 'COMPETITION'

DISTANCE FROM WINDBREAK	DRY WEIGHTS (t ha^{-1}) grain	stover	panicle	total
3 m **unpruned**	1.354	4.181	2.252	6.432
8 m	1.103	3.573	2.046	5.618
13 m	1.222	3.671	2.181	5.851
18 m	1.086	3.450	1.962	5.412
23 m	1.220	3.384	2.217	5.601
33 m	1.107	3.260	2.049	5.309
43 m	0.975	3.194	1.828	5.022
53 m	1.032	3.918	1.905	5.823
mean	1.137	3.579	2.055	5.633
3 m **pruned**	1.251	5.370	2.271	7.641
8 m	1.042	3.582	2.011	5.593
13 m	1.105	3.904	2.005	5.909
18 m	0.913	2.998	1.782	4.780
23 m	1.309	3.804	2.385	6.190
33 m	1.056	3.057	1.995	5.053
43 m	0.822	2.526	1.650	4.177
53 m	1.309	3.819	2.293	6.112
mean	1.101	3.634	2.049	5.682
s.e. (*n* = 96)	0.030	0.112	0.041	0.137

DISTANCE FROM WINDBREAK	1000 grain Weight (g)	Harvest Index	No. full panicle (10^3)	Weight of panicle (g)
3 m **unpruned**	8.00	0.213	53.13	25.5
8 m	7.73	0.195	57.76	19.0
13 m	7.93	0.212	58.64	20.7
18 m	7.38	0.198	52.91	20.4
23 m	8.28	0.215	51.91	24.3
33 m	7.82	0.208	54.22	20.0
43 m	7.65	0.195	51.65	19.1
53 m	7.25	0.180	51.19	18.0
mean	7.76	0.202	54.68	20.9
			continued	
3 m **pruned**	8.10	0.170	59.13	21.0
8 m	7.62	0.187	57.18	18.4
13 m	7.88	0.187	57.31	19.5
18 m	6.80	0.192	55.15	16.5
23 m	7.33	0.220	58.17	22.7
33 m	6.95	0.210	57.23	18.4
43 m	7.02	0.193	49.16	16.4
53 m	7.60	0.213	59.42	22.1
mean	7.31	0.196	56.62	19.4
s.e. (*n* = 96)	0.08	0.003	0.87	0.5

TABLE II.15 'DENSITY'

DISTANCE FROM WINDBREAK	DRY WEIGHTS ($t\ ha^{-1}$) grain	stover	panicle	total
5 m east - open	0.374	2.514	1.028	3.542
15 m	0.285	1.610	0.695	2.305
30 m	0.396	2.037	0.940	2.977
50 m	0.604	3.336	1.447	4.782
mean	0.415	2.374	1.027	3.401
5 m east - dense	0.367	2.445	1.007	3.453
15 m	0.558	2.218	1.123	3.341
30 m	0.650	2.925	1.368	4.293
50 m	0.530	2.395	1.218	3.612
mean	0.526	2.496	1.179	3.675
5 m west - open	0.492	2.537	1.126	3.663
15 m	1.008	2.332	1.793	4.125
30 m	0.699	2.352	1.365	3.717
50 m	0.624	1.829	1.205	3.034
mean	0.706	2.262	1.372	3.635
5 m west - dense	0.377	2.029	0.869	2.898
15 m	0.596	1.815	1.207	3.022
30 m	0.706	2.238	1.390	3.628
50 m	0.626	1.386	1.231	2.617
mean	0.576	1.867	1.174	3.042
s.e. ($n = 96$)	0.027	0.088	0.045	0.127

DISTANCE FROM WINDBREAK	1000 grain Weight (g)	Harvest Index	No. full panicle (10^3)	Weight of panicle (g)
5 m east - open	7.50	0.108	32.33	11.6
15 m	6.95	0.123	23.11	13.1
30 m	7.67	0.117	32.11	12.0
50 m	7.95	0.122	46.67	12.7
mean	7.52	0.118	33.55	12.3
5 m east - dense	7.77	0.102	32.78	13.3
15 m	7.72	0.163	37.44	14.7
30 m	7.97	0.148	34.55	18.1
50 m	7.73	0.143	38.22	14.5
mean	7.80	0.139	35.75	15.2

continued

5 m west - open	8.23	0.128	35.88	13.1
15 m	9.25	0.245	51.11	19.3
30 m	8.67	0.187	41.88	16.7
50 m	8.90	0.243	37.11	16.5
mean	8.76	0.201	41.50	16.4
5 m west - dense	7.57	0.128	28.89	13.0
15 m	8.75	0.190	32.45	17.8
30 m	8.82	0.187	41.56	16.4
50 m	8.62	0.262	35.66	18.7
mean	8.44	0.191	34.64	16.4
s.e. (*n* = 96)	0.08	0.006	1.49	0.4

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TABLE II.16 'STANDARD'

DISTANCE FROM WINDBREAK		DRY WEIGHTS (t ha^{-1})		
	grain	stover	panicle	total
3.21 east	0.325	1.631	0.792	2.424
5.46	0.764	2.773	1.549	4.323
7.60	1.256	3.147	2.051	5.198
9.85	1.318	3.015	2.167	5.181
12.10	1.134	2.961	2.037	4.998
14.35	1.041	3.267	1.939	5.206
16.60	1.219	2.942	2.163	5.106
18.26	1.073	3.014	1.846	4.860
24.00	1.238	3.147	2.243	5.390
30.00	1.280	3.280	2.348	5.628
36.00	1.051	2.468	1.824	4.291
42.00	1.414	2.822	2.327	5.149
48.00	1.056	2.203	1.835	4.038
60.00	1.091	2.410	1.855	4.266
90.00	0.643	2.325	1.494	3.819
120.00	0.594	1.692	1.279	2.971
mean	1.031	2.694	1.859	4.553
s.e. (*n* = 80)	0.030	0.082	0.039	0.109

continued

2.68 west	0.510	1.333	0.947	2.279
4.88	0.814	1.960	1.407	3.367
7.13	0.924	1.667	1.541	3.208
9.37	1.096	1.805	1.820	3.625
11.63	0.978	1.723	1.661	3.384
13.87	1.044	1.796	1.789	3.585
16.13	1.113	2.070	1.844	3.913
18.38	1.306	1.819	2.094	3.910
24.00	0.923	1.792	1.618	3.408
36.00	1.221	1.505	1.903	3.409
60.00	1.037	1.490	1.832	3.323
mean	0.997	1.724	1.678	3.402
s.e. (n = 55)	0.041	0.069	0.058	0.118
control	0.938	1.981	1.572	3.554

DISTANCE FROM WINDBREAK	1000 grain Weight (g)	Harvest Index	No. full panicle (10^3)	Weight of panicle (g)
3.21 east	5.16	0.130	26.06	11.7
5.46	6.67	0.175	45.40	16.5
7.60	5.44	0.240	48.84	25.8
9.85	7.14	0.251	58.79	22.5
12.10	6.71	0.239	54.07	21.0
14.35	7.00	0.206	53.62	19.6
16.60	7.49	0.238	56.21	21.8
18.26	6.91	0.222	47.45	22.3
24.00	6.99	0.230	57.02	21.9
30.00	7.42	0.228	52.49	25.0
36.00	6.74	0.248	50.68	21.0
42.00	7.23	0.276	57.74	24.4
48.00	6.56	0.263	49.54	21.4
60.00	6.31	0.267	50.63	21.2
90.00	4.65	0.167	55.00	11.7
120.00	5.36	0.200	44.87	13.3
mean	6.49	0.224	50.53	20.1
s.e. (n = 80)	0.16	0.005	1.09	0.4

continued

2.68 east	5.75	0.181	28.51	15.0
4.88	6.66	0.249	39.68	20.6
7.13	5.38	0.286	47.57	19.4
9.37	6.90	0.301	42.28	26.2
11.63	7.35	0.293	38.41	25.5
13.87	7.74	0.296	44.18	23.6
16.13	5.75	0.279	49.54	23.5
18.38	7.98	0.333	46.59	28.6
24.00	8.15	0.258	38.08	23.1
36.00	7.39	0.360	48.19	25.4
60.00	5.21	0.313	60.52	17.6
mean	6.79	0.286	43.96	22.6
s.e. ($n = 55$)	0.27	0.007	1.42	0.8
control	7.27	0.267	36.24	25.9

TABLE II.17 'COMPETITION'

DISTANCE FROM		DRY WEIGHTS (t ha^{-1})		
WINDBREAK	grain	stover	panicle	total
3.56 **unpruned**	0.331	1.812	0.848	2.659
5.81	0.688	3.049	1.395	4.444
7.95	0.638	2.288	1.356	3.644
10.21	1.118	3.134	1.950	5.084
12.45	0.885	2.921	1.707	4.628
14.71	0.852	2.694	1.643	4.337
16.96	1.032	3.307	2.089	5.396
18.61	1.063	3.010	1.944	4.953
mean	0.826	2.777	1.616	4.393
3.65 **pruned**	0.567	2.696	1.124	3.820
5.89	0.777	3.215	1.582	4.797
8.04	0.811	2.869	1.558	4.427
10.29	1.033	3.269	2.041	5.310
12.54	0.985	3.119	1.840	4.959
14.79	0.857	2.948	1.672	4.620
17.05	1.026	3.350	1.951	5.301
18.69	1.017	3.009	1.903	4.912
mean	0.884	3.059	1.709	4.768
s.e. ($n = 96$)	0.033	0.113	0.055	0.160

DISTANCE FROM WINDBREAK	1000 grain Weight (g)	Harvest Index	No. full panicle (10^3)	Weight of panicle (g)
3.56 **unpruned**	6.80	0.113	23.57	12.7
5.81	6.45	0.170	38.11	17.9
7.95	6.59	0.176	35.08	17.3
10.21	6.55	0.220	49.87	22.0
12.45	6.67	0.198	42.45	20.8
14.71	6.61	0.197	39.70	21.3
16.96	6.75	0.193	48.45	21.2
18.61	6.51	0.213	47.75	21.8
mean	6.62	0.185	40.62	19.4
3.65 **pruned**	6.45	0.141	27.46	20.0
5.89	6.09	0.161	42.33	18.0
8.04	7.03	0.185	39.85	19.7
10.29	6.39	0.202	47.36	22.2
12.54	6.37	0.201	47.82	20.5
14.79	6.48	0.179	39.11	21.2
17.05	6.69	0.192	51.06	20.0
18.69	6.56	0.200	49.17	20.9
mean	6.51	0.183	43.02	20.3
s.e. (n = 96)	0.06	0.005	1.21	0.5

TABLE II.18 'DENSITY'

DISTANCE FROM WINDBREAK	grain	DRY WEIGHTS (t ha^{-1}) stover	panicle	total
3.21 **east - open**	0.288	1.633	0.685	2.318
5.46	0.578	2.257	1.115	3.373
7.61	0.735	2.486	1.277	3.764
9.86	0.766	2.388	1.387	3.775
12.11	0.691	2.699	1.462	4.160
14.36	0.640	2.688	1.296	3.984
16.61	0.601	2.424	1.299	3.723
18.25	0.713	2.688	1.260	3.948
24.00	0.733	2.022	1.340	3.362
30.00	0.726	2.762	1.438	4.199
36.00	0.582	2.176	1.228	3.404
42.00	0.820	2.044	1.433	3.477
48.00	0.638	2.127	1.232	3.360
60.00	0.570	2.001	1.150	3.151
90.00	0.350	2.196	1.142	3.338
120.00	0.447	2.109	1.096	3.205
mean	0.617	2.294	1.240	3.534
3.23 **east - dense**	0.201	1.751	0.617	2.368

5.48	0.661	2.755	1.242	3.997
7.63	0.649	2.361	1.219	3.580
9.88	0.763	2.583	1.372	3.955
12.13	0.711	2.385	1.328	3.713
14.38	0.726	2.897	1.346	4.242
16.63	0.800	2.561	1.451	4.011
18.28	0.783	2.438	1.524	3.962
24.00	0.726	2.031	1.343	3.374
30.00	0.716	2.444	1.333	3.777
36.00	0.711	2.053	1.391	3.444
42.00	0.646	2.067	1.249	3.317
48.00	0.631	2.122	1.196	3.317
60.00	0.569	2.054	1.226	3.280
90.00	0.408	2.078	1.196	3.274
120.00	0.450	2.430	1.067	3.497
mean	0.634	2.313	1.256	3.569
s.e. (n = 128)	0.033	0.074	0.047	0.113
3.69 west - open	0.414	1.498	0.805	2.304
5.93	0.359	1.275	0.684	1.959
8.18	0.777	2.588	1.451	4.039
10.43	0.836	2.404	1.460	3.864
12.68	0.788	2.820	1.440	4.260
14.93	0.769	2.687	1.315	4.002
17.18	0.766	2.143	1.401	3.544
19.43	0.848	2.237	1.515	3.752
24.00	0.951	2.541	1.661	4.202
36.00	0.817	2.093	1.387	3.481
mean	0.760	2.102	1.358	3.460
3.65 west - dense	0.329	1.203	0.696	1.898
5.88	0.528	1.724	0.977	2.701
8.13	0.836	2.529	1.531	4.059
10.38	0.841	2.465	1.513	3.978
12.63	0.806	2.602	1.460	4.063
14.88	0.961	2.643	1.631	4.274
17.13	0.883	2.241	1.524	3.764
19.38	0.817	2.473	1.427	3.900
24.00	0.779	2.287	1.486	3.773
36.00	0.865	2.242	1.478	3.720
mean	0.741	2.173	1.341	3.514
s.e. (n = 80)	0.034	0.061	0.047	0.085

DISTANCE FROM WINDBREAK	1000 grain Weight (g)	Harvest Index	No. full panicle (10^3)	Weight panicle (g)
3.21 **east - open**	6.54	0.114	20.57	12.5
5.46	6.96	0.159	33.15	16.3
7.61	5.34	0.172	35.19	18.5
9.86	5.28	0.174	39.91	16.8
12.11	6.20	0.153	38.54	17.1
14.36	6.40	0.154	40.58	15.2
16.61	6.43	0.155	38.91	15.0
18.25	6.46	0.172	37.03	17.9
24.00	6.96	0.212	37.37	18.6
30.00	5.00	0.171	37.18	19.8
36.00	4.74	0.172	40.08	14.8
42.00	5.07	0.224	36.82	21.3
48.00	6.56	0.184	30.86	20.1
60.00	6.49	0.196	33.58	17.2
90.00	5.97	0.102	34.17	9.8
120.00	4.38	0.142	34.07	14.7
mean	5.99	0.166	35.50	16.6
3.23 east - dense	6.59	0.075	16.63	10.8
5.48	6.67	0.166	38.87	16.9
7.63	6.62	0.177	32.51	19.6
9.88	6.65	0.183	43.03	17.0
12.13	6.60	0.178	40.05	16.4
14.38	6.52	0.167	34.36	19.8
16.63	6.51	0.188	40.37	19.0
18.28	4.39	0.189	42.92	17.4
24.00	6.70	0.216	32.64	22.2
30.00	6.67	0.184	34.73	19.6
36.00	5.61	0.180	33.59	19.0
42.00	6.38	0.191	39.11	16.1
48.00	6.35	0.202	30.75	20.8
60.00	6.88	0.183	31.31	17.5
90.00	5.81	0.133	41.13	10.2
120.00	6.13	0.130	32.95	13.8
mean	6.32	0.171	35.31	17.2
s.e. (n = 128)	0.14	0.004	1.10	0.4

continued

3.69 west - open	6.42	0.153	22.18	14.8
5.93	5.66	0.170	21.76	15.8
8.18	7.04	0.195	39.39	20.7
10.43	6.42	0.219	40.33	20.5
12.68	6.83	0.179	39.68	19.1
14.93	6.26	0.203	42.30	18.2
17.18	6.86	0.215	40.73	18.5
19.43	6.98	0.220	38.68	22.1
24.00	6.69	0.217	45.69	19.9
36.00	6.33	0.244	35.40	23.5
mean	6.55	0.219	39.05	19.1
3.65 west - dense	6.78	0.140	19.03	15.0
5.88	6.10	0.183	25.84	19.2
8.13	7.26	0.212	40.50	20.7
10.38	7.29	0.210	42.35	19.6
12.63	5.37	0.195	41.22	19.1
14.88	5.66	0.221	43.90	21.6
17.13	6.45	0.234	42.07	20.5
19.38	6.41	0.214	41.94	19.6
24.00	7.16	0.200	39.68	19.6
36.00	4.78	0.229	42.90	19.6
mean	6.33	0.203	38.12	18.8
s.e. (*n* = 80)	0.17	0.007	0.89	0.6

APPENDIX III

THE DESIGN AND CONSTRUCTION OF A LOW COST PSYCHROMETER FOR MICROMETEOROLOGICAL MEASUREMENTS.

SUMMARY

Construction details and design features of a robust, low-cost ventilated psychrometer are described. The psychrometer gave good results when tested against an Assmann psychrometer under the extreme conditions of the Sahel.

INTRODUCTION

The measurement of humidity is necessary in many micrometeorological experiments. The sensors required for this type of work need to be:

(i) Cheap to construct as several sensors are often required for adequate replication.

(ii) Accurate, since differences being investigated are often small, especially in Bowen ratio measurements.

(iii) Easily constructed and maintained, so that advanced technical facilities or return to the manufacturer are not required. This may be especially important in developing countries.

(iv) Reliable under severe field conditions, eg. arid, tropical or cool temperate environments.

(v) Easily connected to an automatic data-logger.

There are many sensors available for the measurement of humidity (Rundell and Jarrell, 1989). These fall into five categories, psychrometric, absorption, condensation, electrochemical, and radiation absorption. Of these, the psychrometric (wet bulb/dry bulb psychrometer), electrochemical (capacitance sensor), radiation absorption (infra-red gas analyser) and condensation methods (dew-point meters) are the most suitable for field use. The gas analyser is normally too expensive for applications requiring a large number of sensors and too complex to allow easy field maintenance. Capacitance probes are often used, but may not be sufficiently accurate for many micrometeorological applications. They are also easily damaged by dust or condensation of water on the plates. Dew-point meters have been used successfully for Bowen ratio measurements, but are expensive and encounter problems when dust settles on the mirrors. The psychrometer is the only type of sensor capable of meeting the full range of specifications listed above.

Currently there is no low cost commercially available units that meets all the requirements. Low cost psychrometers have been described by Lourence and Pruitt (1969), Rosenberg and Brown (1974), and Munro (1980), however all the psychrometers above required advanced workshop facilities for construction. This paper describes an easily constructed wet-and-dry bulb psychrometer designed to fill this gap in the available range of instruments.

INSTRUMENT DESCRIPTION

General Description

The body of the psychrometer was constructed from materials available in Do-It-Yourself shops for plumbing. There were three pieces of plastic piping (Figure III.1); a sediment trap (British Standard 3943, McAlpine Ltd.) used in domestic plumbing to collect sediment in waste outflow from wash-hand basins (1) serves as a double radiation shield contained the sensors. This was attached to a straight piece of piping (4) upon which the water bottle was mounted, and containing the fan with a right angle bend (6) attached to the other end. The air flowed past two sensors measuring the air temperature and the wet bulb depression, down the horizontal air flow pipe through the fan, and out through the exhaust bend, (see arrows on Figure III.1).

Sensors

The two sensors were mounted on an acrylic plastic 'Perspex' former (see Figure III.1, view B), covered with aluminium foil to minimise radiation coupling between the wet and dry bulbs. The sensor former (2), was constructed from 2 mm thick 'Perspex', and fitted in the central part of the bottle trap. View (C) shows the

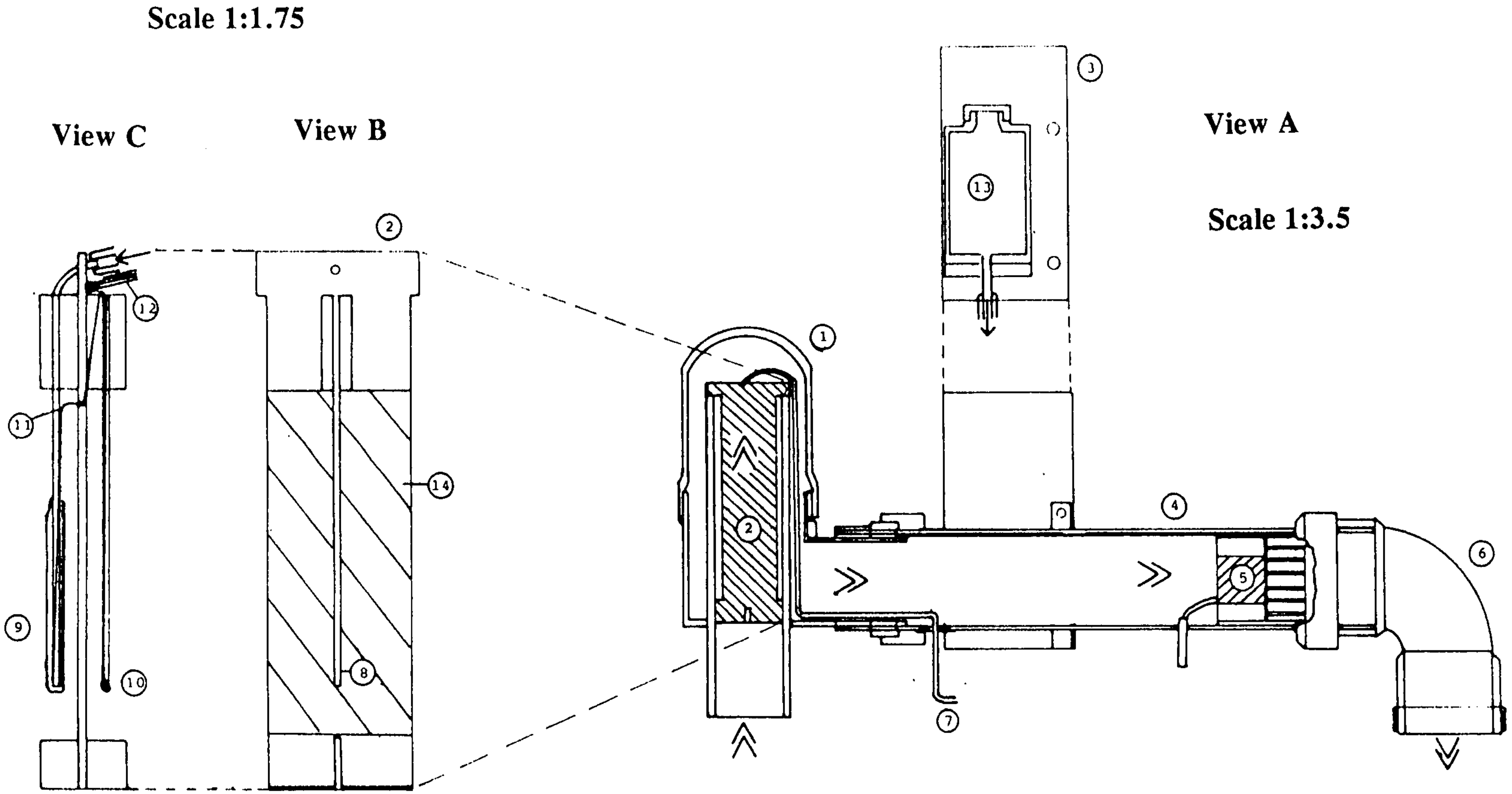

Figure III.1 Cross-section (View A) of a low cost psychrometer. Air moves up the intake of the sediment trap (1), past the 'Perspex' former (2) which holds the sensors (View B and C), down the horizontal air flow pipe (4), through the fan (5), and out through the right angle exhaust bend (6). Water is supplied to the wet bulb (9) via a polythene tube (7), from a plastic bottle (13), attached to a holder (3). The former (2) (view B) is covered with aluminium foil (14), and holds two plastic tubes, (View C), one measuring air temperature with a thermistor (10), and the other the wet bulb depression with a thermocouple (11). Full details are given in the text.

side view of the sensor former. The air temperature was sensed with a 10 kΩ thermistor (10), (Fenwall Unicurve C-UVA41JI, Electrautom Ltd., Aylesford, UK) mounted at the end of a 70 mm, rigid 1.5 mm plastic tube (8), to reduce the conduction error. In this model a thermistor was used to measure dry bulb temperature in order to enable the psychrometer to record at a considerable distance from the logger, without being dependent on a reference temperature, as in the Lourence and Pruitt (1969) model. The sensor wires (0.1 mm diameter enamelled copper wire) inside the plastic tube were soldered to 0.2 mm signal wire, and the junction was glued onto the 'Perspex' former. The wet bulb depression was sensed with a copper-constantan thermocouple (11), (0.1 mm diameter, Dural Plastics Inc., Australia), with one thermojunction attached to the dry bulb thermistor and the second to the wet bulb, which consisted of an identical plastic tube with a cotton wick (9) tied over the end.

The positioning of the former allowed the sensors to measure the air as it first entered the psychrometer. Air entered the psychrometer vertically upwards, which was an advantage in areas prone to sand storms since the intake of wind blown dust is reduced.

Water delivery system

Distilled water was transported to the wet bulb via a small polythene tube (7), (2 mm diameter.) connected to a plastic reservoir (13), mounted on the side of the horizontal airflow pipe of the psychrometer. The water travelled through this tube to the rigid plastic tube covered by the wick, the distance travelled along the tube within the psychrometer, allows the water to come to equilibrium with air temperature, reducing the error caused by the transport of hot water to the wet bulb. The delivery of water to the point of evaporation, rather than relying on the conduction along a long piece of wick, and ability to adjust level of the water reservoir to provide a slight positive pressure reduced the possibility of the wick partially drying under extremely dry conditions, a problem that has been noted with other models in the Sahel. The size of the reservoir can be altered according to the ambient humidity and the frequency of replenishment.

Ventilation

Ventilation was provided by a 12 V D.C. fan (5), (U36IL 012DC, Micronel, Zurich, Switzerland), which sucked air past the sensors along the horizontal airflow pipe at a velocity of 4.0 m s^{-1}. The fan was connected to the external cabling via a screw terminal block to allow easy replacement in the field. The lifetime of fans depended on environmental conditions, running continuously in adverse environments, such as the Sahel, it typically lasted for 6 months, and consumed about 0.06 A current.

Wiring

The cable carrying the sensors' signals was shielded 4-core (0.2 mm diameter.) copper cable (RS Components, Ltd. U.K.). One pair connected the dry-bulb thermistor to the data-logger and the other the thermocouple measuring the wet-bulb depression. The fan was connected to a 12 V lead-acid battery by a separate pair of 0.5 mm diameter copper 1 amp flex.

VALIDATION

To test the accuracy of the psychrometer its performance was compared in the field with that of an Assmann ventilated psychrometer (Clockwork, with mercury in glass thermometers, Cassella Ltd., London), a standard meteorological instrument for spot measurements of humidity. The output from the wet and dry bulb sensors were recorded every half hour with a solid-state data-logger (CR21X, Campbell Scientific Inc., Logan). During this period relative humidities ranged from 10% to 35%, with short wave radiation loads of up to 900 W m^{-2}.

Figure III.2 shows the time course of air temperature measured with three low cost psychrometers and with the Assmann psychrometer. There was good agreement (to within 0.5 ^{o}C) between the two types of instrument, especially during the middle of the day. During the morning the low cost psychrometers recorded a slightly higher air temperature than the Assmann, but in the afternoon the difference was reversed. Rosenberg and Brown (1974) observed a difference of 0.7 ^{o}C between the Assmann and their psychrometer, with the Assmann recording up to 1.5 ^{o}C higher dry bulb temperatures.

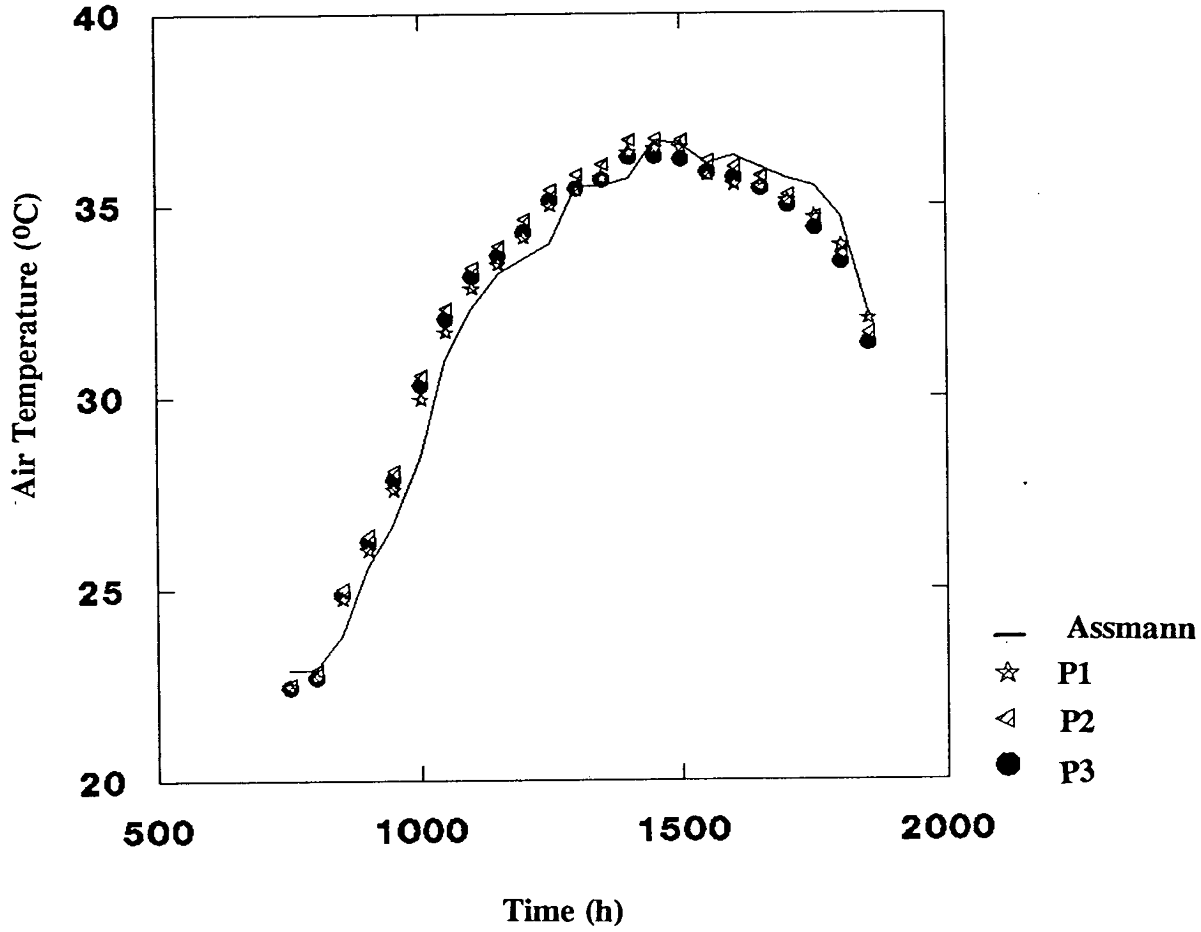

Figure III.2. Time series plot of air temperature measured by 3 low cost psychrometer (P1, P2, and P3), compared to that measured by an Assmann psychrometer (——), over a day in Niger.

Mean air temperature measured with the low cost psychrometers plotted against air temperature measured with the Assmann in chronological order (Figure III.3), revealed distinct hysteresis in the relationship. This may result from the thermal inertia of the Assmann (conferred by its weighty metal casing) causing the temperature of this instrument to lag somewhat behind the rapid changes in ambient temperature experienced during the test. The low cost psychrometer has a much lower mass, allowing its body temperature to track air temperature more closely.

Figure III.4 shows fairly good agreement between the wet bulb temperatures of the two types of psychrometers, with the majority of points falling below the 1:1 line. Thus even under very dry conditions the wet bulb depression of the low cost psychrometer was larger, suggesting superior performance to that of the Assmann. Rosenberg and Brown (1974), reported smaller wet bulb depressions than the Assmann. The average difference in calculated vapour pressure measured between the low cost and Assmann psychrometers was -0.075 ± 0.08 kPa (n = 22). So the low cost psychrometer by estimating, a larger wet bulb depression, functioned as well if not better than the Assmann.

CONCLUSIONS

The low cost psychrometer has been satisfactorily used in a range of remote sites, and extreme environments, in the Highlands of Scotland (Grace *et al.*, 1989), Saudi Arabia (Alyemeny, 1989), and in Niger. It provided accurate measurements of humidity, and has proved durable and easy to maintain. The low cost psychrometer compared well with the Assmann, and where discrepancies were observed, the errors were larger in the Assmann than in the low cost model. The instrument was cheap to construct, materials costing around £30 per unit. It has been routinely used with solid-state data-loggers, providing a trouble free, continuous record of atmospheric humidity.

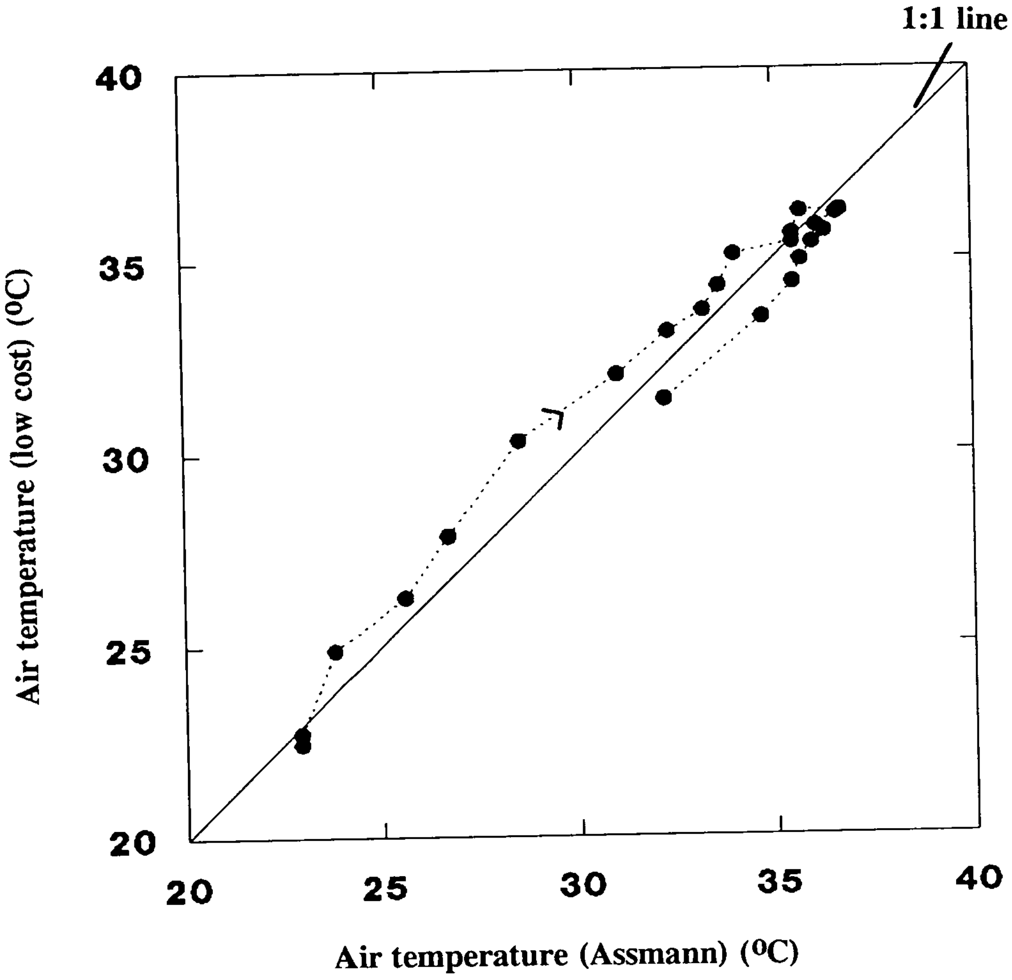

Figure III.3. Comparison of air temperature measured with low cost and Assmann psychrometers. Points linked in chronological order, for a day in Niger.

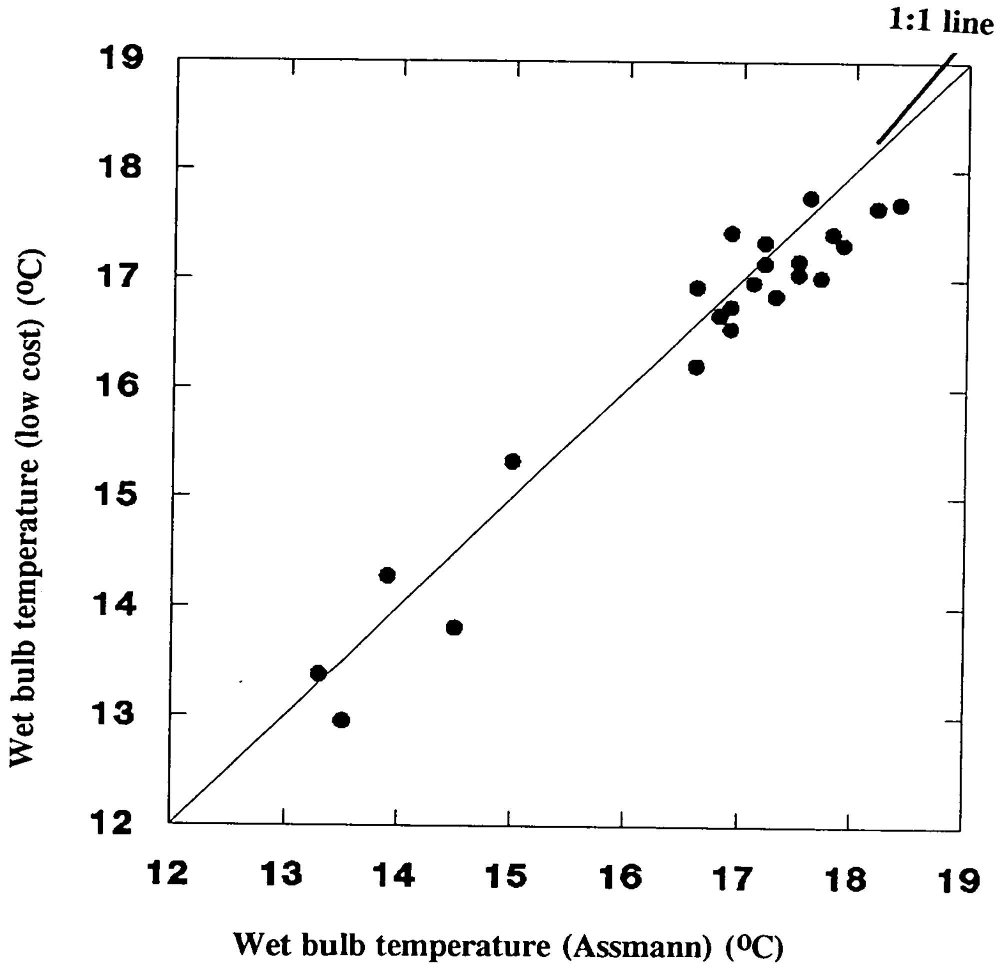

Figure III.4. Comparison of wet bulb temperatures measured by low cost and Assmann psychrometers, for a day in Niger

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APPENDIX IV

A HEATED LEAF REPLICA TECHNIQUE FOR DETERMINATION OF LEAF BOUNDARY LAYER CONDUCTANCE IN THE FIELD.

Introduction

The difficulty in obtaining values of leaf boundary layer conductance in the field may limit accurate determination of latent and sensible heat fluxes from leaves. The conductance between leaf surface and air is a combination of the conductance of the laminar sub-layer close to the surface of the leaf and the turbulent boundary layer slightly further away (Grace, 1977). For most purposes these two conductances can be combined and will be referred to as the boundary layer conductance (g_a).

Leaf g_a results from a combination of two components, (i) free convection where energy is transferred by gradients of temperature creating gradients of density, and (ii) forced convection, where energy transfer is caused by drag exerted by a surface on air flowing over it (Monteith and Unsworth, 1990). It has been suggested that the combination of free and forced convection components can be treated as conductances in parallel (Van Gardingen and Grace, 1991). Values of these conductances can be estimated from engineering equations based on leaf dimensions and wind speeds (eqs. IV.12 and IV.13) (Kreith, 1973) and predict transfer reasonably well under laminar flow conditions (Dixon and Grace, 1984; Grace, 1983), however g_a for real leaves in the field may be substantially underestimated (Monteith, 1981) and consequently it is best to make direct mesurements.

Background to methods

Water transfer

Rates of water loss from a blotting paper leaf replica saturated with distilled water have been used to calculate the boundary layer conductance for water vapour (g_a^v) (Gaastra, 1959; Grace and Wilson, 1976; Azam-Ali, 1983). This method requires careful measurements of the change of weight before and after exposure to wind, time the replica was exposed and vapour pressure of the air and at the replica surface. Errors g_a^v using this technique could be as high as 45 % (Grace and Wilson, 1976) resulting from loss of water while not under test conditions, and uncertainty associated with measurement of surface temperature.

Heat Transfer

The boundary layer conductance for heat transfer (g_a^h) can in most field applications be assumed to equal g_a^v. Tibballs *et al.* (1964) used silver castings of conifer shoots to determine leaf heat transfer coefficient, heating the models > 30 K above ambient temperature, and measuring the rate of heat loss. The low emissivity (ϵ) of the silver surface reduced the energy loss by radiation. Convective heat loss from a surface is given by IV.1:

$$H = \rho_a C_p (T_s - T_a) g_a^h \qquad \text{(IV.1)}$$

where H is sensible heat loss, ρ_a is density of air, C_p is specific heat capacity of air at constant pressure, and $(T_s - T_a)$ is replica surface to air temperature difference.

Grace *et al.* (1980) measured cooling rates of brass replicas, to estimate g_a^h of a tropical tree using equation IV.2, ('transient' leaf replica method).

$$g_a^h = (C_b \, m \, b)/(\rho_a C_p A_t) \qquad \text{(IV.2)}$$

where C_b is specific heat of brass, m mass of replica, b slope of the regression of the logarithm of the leaf-air temperature difference against time, and A_t total surface area of the replica.

Although this method does not take into account radiation errors, the replicas were polished reducing ϵ to 0.1 and radiation errors to 7 %. Dixon (1982) used this method to demonstrate the importance of leaf shape, size and morphology on g_a^h.

Leuning (1989) described a robust 'steady-state' field technique using a pair of leaf replicas, explained below.

The energy balance of a leaf replica is given by equations IV.3 and IV.4;

$$R_{\mathrm{nin}} = S_{\mathrm{t}}(1 - \alpha) + L_{\mathrm{a}} - L_{\mathrm{e}} \tag{IV.3}$$

$$R_{\mathrm{nout}} = \rho a \; C_p \; (T_{\mathrm{s}} - T_{\mathrm{a}}) \; g_{\mathrm{a}}^{\mathrm{h}} \tag{IV.4}$$

where R_{nin} is radiant energy influx, R_{nout} is convective energy leaving the plate, S_{t} is incoming solar energy, α is solar reflectance, and L_{a} and L_{e} are absorbed and emitted long-wave radiation. Assuming that changes in energy storage of the leaf replica are small at steady-state then;

$$R_{\mathrm{nin}} = R_{\mathrm{nout}} \tag{IV.5}$$

Consider now two replicas with the same area, surface properties (ϵ and α), and boundary layer conductance. If replica 1 is heated with power input P_{e} the energy balance for the two replicas is as follows;

Replica 1 $\quad R_{\mathrm{n1}} + P_{\mathrm{e}} = \rho a \; C_p \; (T_{\mathrm{s1}} - T_{\mathrm{a}}) \; g_{\mathrm{a}}^{\mathrm{h}}$ (IV.6)
Replica 2 $\quad R_{\mathrm{n2}} = \rho a \; C_p \; (T_{\mathrm{s2}} - T_{\mathrm{a}}) \; g_{\mathrm{a}}^{\mathrm{h}}$ (IV.7)

where R_{n1} and T_{s1}, and R_{n2} and T_{s2}, are the net radiation influx and surface temperatures of replicas 1 and 2 respectively. Subtracting equations IV.6 from IV.7 gives;

$$R_{\mathrm{n1}} + P_{\mathrm{e}} - R_{\mathrm{n2}} = \rho a \; C_p \; (T_{\mathrm{s1}} - T_{\mathrm{s2}}) \; g_{\mathrm{a}}^{\mathrm{h}} \tag{IV.8}$$

If it is assumed that $R_{\mathrm{n1}} = R_{\mathrm{n2}}$ then,

$$g_{\mathrm{a}}^{\mathrm{h}} = P_{\mathrm{e}} \, / \, \rho a \; C_p \; (T_{\mathrm{s1}} - T_{\mathrm{s2}})) \tag{IV.9}$$

So with a known heat input and a measure of the temperature difference between the two replicas g_a^h can be calculated.

Equation IV.9 is based on the assumption of $R_{n1} = R_{n2}$, but the replicas are at different temperatures, thus L_e will be different for the two replicas. This can be corrected for by calculating the difference in L_e between the two replicas as follows;

$$\delta L_e = \epsilon\, \sigma\, (T_{s1}^4 - T_{s2}^4) \qquad \text{(IV.10)}$$

where δL_e is difference in long-wave radiation emitted, and σ is the Stefan-Boltzman constant. The error introduced by ignoring changes in L_e this with a temperature difference of 10 °C and $\epsilon = 0.1$ at 30 °C is about 6 W m^{-2}, this may cause an error in g_a^h of the order of 3 %.

A second error associated with the assumption of $R_{n1} = R_{n2}$ in the field, is that the replicas may absorb different amounts of S_t (equation IV.3) resulting from shading or dirt, which may cause substantial errors in the measurement, a method for compensating for this is outlined later.

Power input to the replicas was calculated from;

$$P_e = (i^2\, r)/\, A_t \qquad \text{(IV.11)}$$

where i is current in the circuit, and r is the electrical resistance of the heating element. The g_a^h of the replica can be calculated using Equations IV.9, IV.10, and IV.11.

Other Methods

Mass transfer analogue techniques such as measuring the rate of sublimation of naphthalene (Neal, 1975), have been used to calculate g_a, but are difficult to record automatically, would need to be corrected for changes in ambient temperature, and could be used only over short time periods.

Calculation of boundary layer conductance for laminar flow

Pathways for water vapour and heat from the surface of a leaf to a reference point are usually assumed to be identical. So conductance across the laminar sub-layer differs by $(D_h / D_v)^{0.66}$ where D_v and D_h are diffusivities of water and heat respectively (Thom, 1968). At 20 °C the ratio of the conductances g_a^h / g_a^v is 0.93 (Grace, 1983).

Forced convection can be calculated using equations in engineering texts for heat transfer with flat plates under laminar flow (Kreith, 1973);

$$g_a^h = (0.66\, D_h^{0.67}\, u^{0.5}) / (d^{0.5}\, v^{0.17}) \qquad \text{(IV.12)}$$

where u is wind speed, d is characteristic dimension of the leaf, and v is kinematic viscosity. Free convection is given by;

$$g_a^h = (0.54 D_h^{0.75} g^{0.25} a_t^{0.25} (T_s - T_a)^{0.25}) / (d^{0.25}\, v^{0.25}) \qquad \text{(IV.13)}$$

where a_t is coefficient of thermal expansion of air, and g is acceleration due to gravity. These equations have been used successfully for predicting g_a for flat non-flapping leaves under laminar flow (Dixon and Grace, 1984).

MATERIAL AND METHODS

Plate construction details

The replicas consisted of two layers of 0.2 mm thick brass shim (30 cm x 3.5 cm), with 90 cm of 0.27 mm diameter enamelled constantan resistance wire (Scientific Wire Company, London, UK), sandwiched between. The wire was insulated from the brass with double sided tape, and epoxy resin. Replicas were nickel plated, to give a high α, and low ϵ.

Replicas were attached to a metal frame 42 cm x 21 cm with nylon fishing line (0.3 mm diameter) see Figure IV.1. Three sets of thermocouples (copper-constantan, type T, Comark Electronics, Rustington, UK) wired in parallel were attached to the underside of the replicas with adhesive aluminium foil (Figure IV.1). Power and signal cables were connected via a 6-way plug, to a lead-acid battery and a data

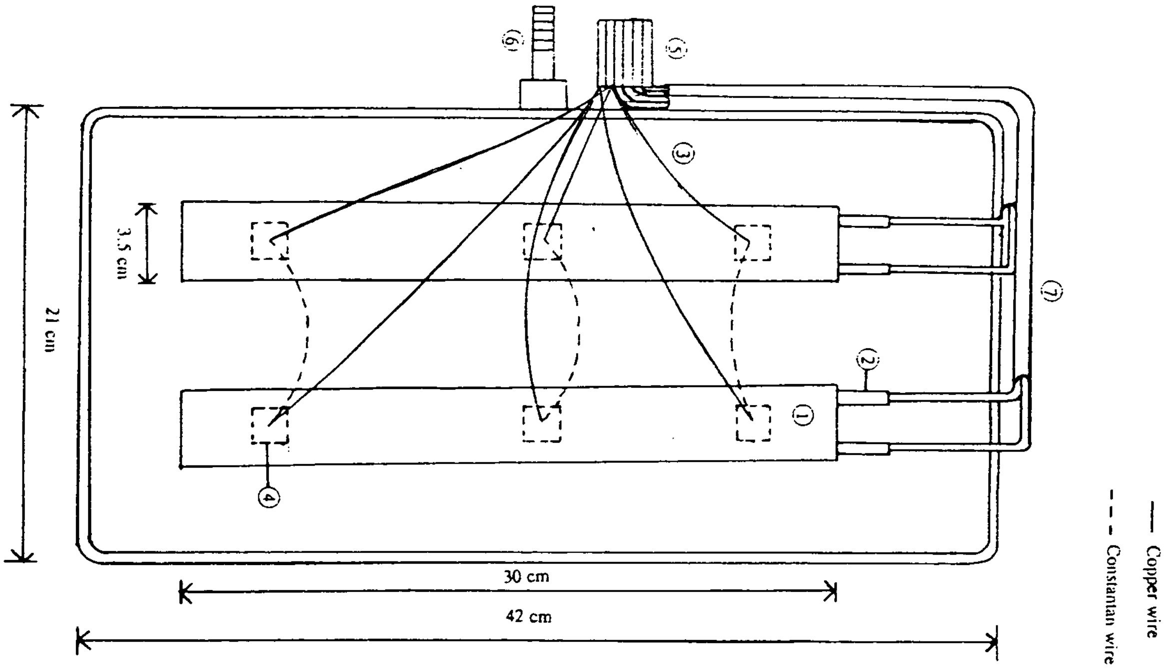


Figure IV.1 Heated leaf replicas 1) were attached to a metal frame, using fishing line. The frame could be attached to a mast via bolt 6). Thermocouples to measure the temperature difference between replicas 3), were stuck to the underside of the replicas using adhesive aluminium foil 4). Power was passed alternately between circuits, via the 6-way cable shell 5), and power cable 7), to the terminals 2) to heat up the replica.

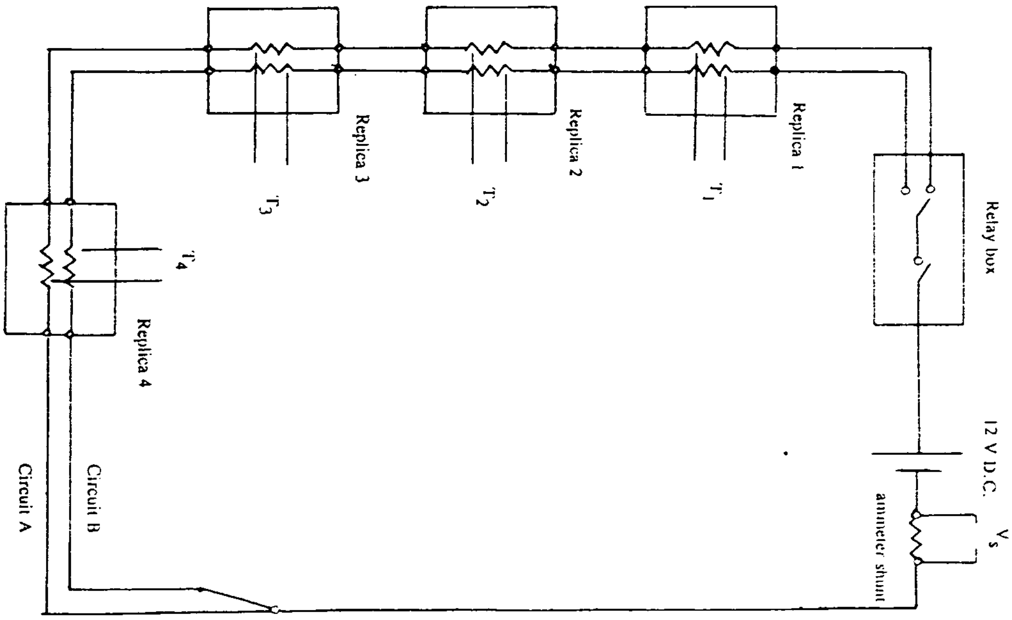


Figure IV.2 The field arrangement consisted of a relay box to switch the current on and off, and switch between circuits, four pairs of thermocouples, and an ammeter shunt. Temperature differences T_1, T_2, T_3, T_4 and voltage V_s were measured using a CR10 logger. The system was powered with a 12 V D.C. battery.

logger respectively (CR10, Campbell Scientific, Logan, Utah, USA).

Circuit Diagrams and field configuration.

Field arrangement consisted of four sets of replicas connected in series, each having a resistance of 10.2 Ω, Figure IV.2. Power was supplied from a 12 V battery, and current calculated from the voltage drop across an ammeter shunt (0.12 Ω), also logged on the CR10.

To eliminate errors from differences in R_{nin} between unheated replicas, a system was developed that allowed the switching of the power on and off. When the power was switched off the temperature difference between the two replicas was taken as an offset. The logger was programmed to heat replicas in circuit A (Figure IV.2) for 15 minutes and measure the temperature difference, the power was switched off for 15 minutes and an offset was measured, then replicas in circuit B were heated for 15 minutes, after which the power was switched off and a second offset was measured, see Figure IV.2. Switching was achieved using a relay box (Figure IV.3), and the control ports on the CR10. Field tests showed replicas required three minutes to reach steady-state after power on, so temperatures were averaged five minutes after power on or power off.

Blotting paper method

Strips of blotting paper 3.5 cm x 30 cm were saturated with distilled water and after excess water had drained placed in a sealed metal container. The container and wet strip were weighed. The strip was removed from it's container and clipped onto nylon thread in a metal frame in the wind tunnel. Two thermojunctions were attached to the paper surface with plastic paper clips and logged on a CR10. Time was recorded between removal and replacement of the paper in its container. Weight of container after removing the strip and on replacement was taken.

WIND TUNNEL VERIFICATION

The technique was tested in a wind tunnel in the Darwin Building at Edinburgh University (details of wind tunnel construction can be found in Dixon, 1982). Experiments were carried out with two initial wind conditions (i) 'initially laminar' where there were no impediments to the incident air flow, and (ii) 'initially

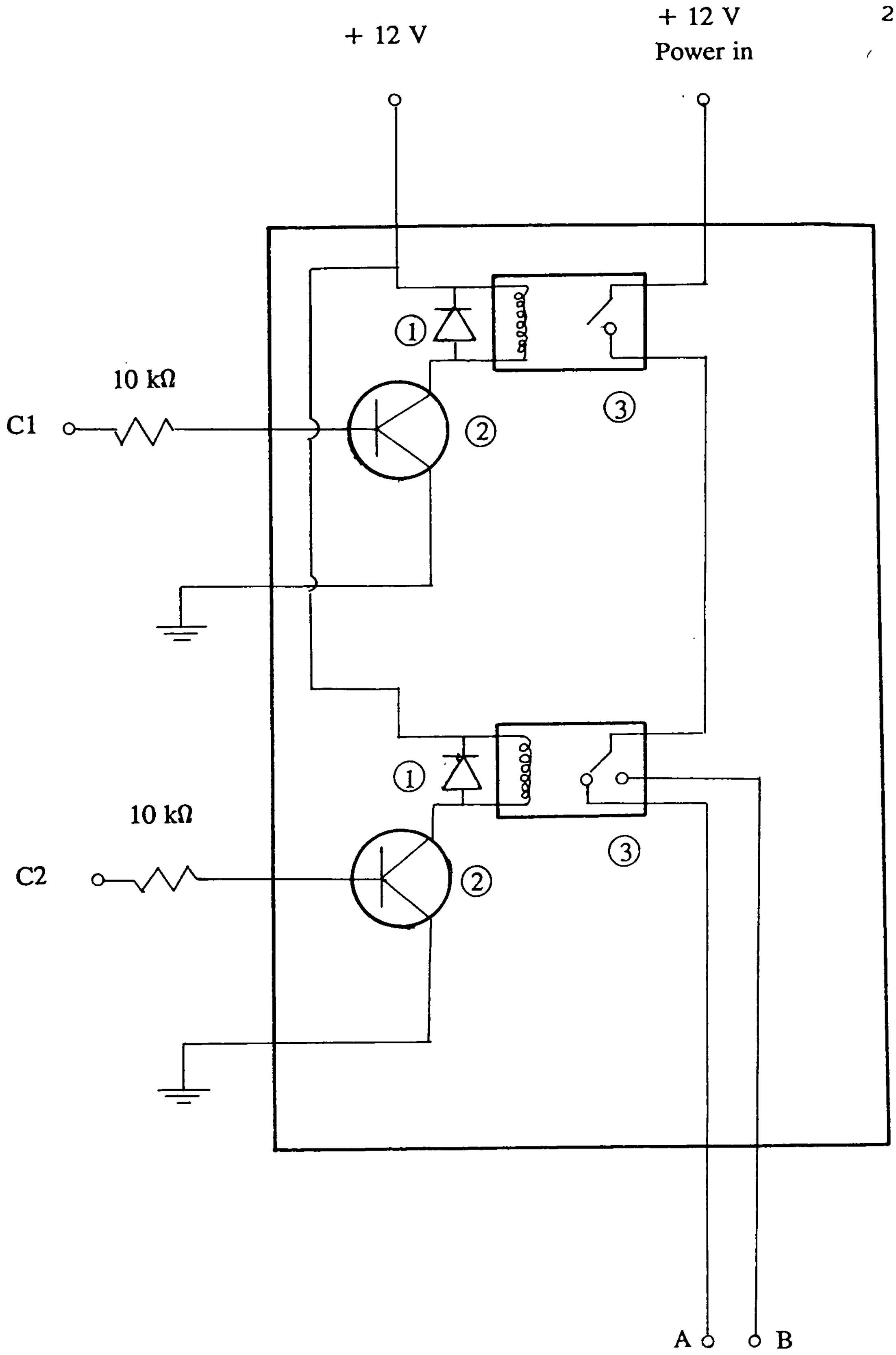


Figure IV.3 Circuit diagram for relay box. Control port 1 (C1) switched power on and off. Control port 2 (C2) switched power between circuits A and B. Other electrical details are given below;

1) Silicon Diode (1N4001)
2) Transistor type E-line trans ZTX600B or MOSFET RFP2N10L GE/RCA
3) 12 V miniature relay (RS. 346-621)

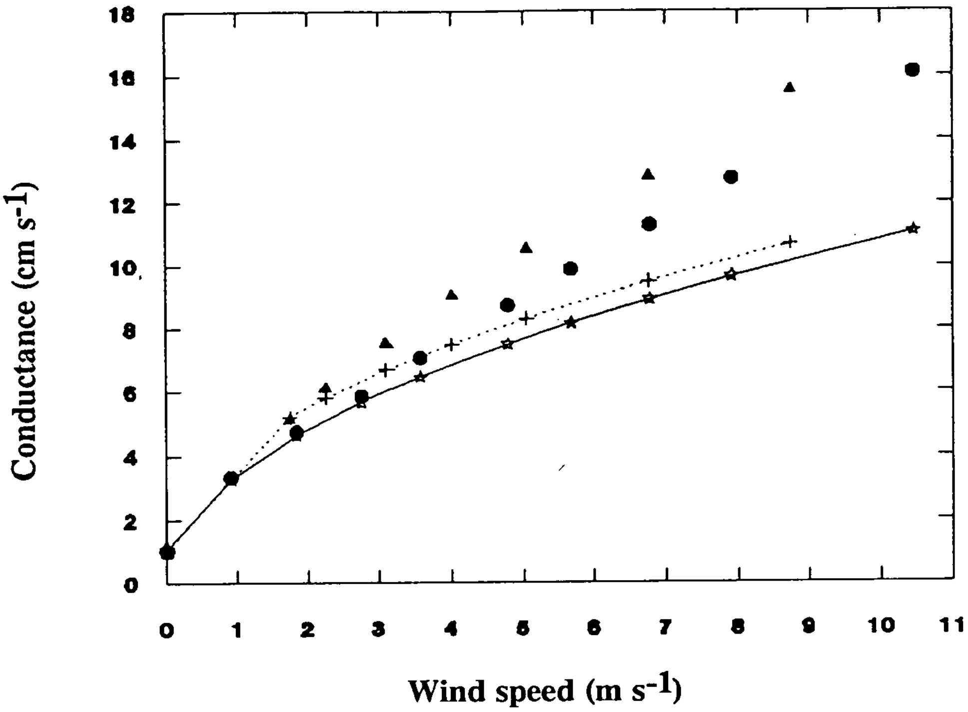
turbulent' where large cross-pieces were placed in the air stream, to create turbulence.

Laminar and turbulent flow

Figure IV.4 shows the relationship between g_a calculated from the equation IV.12 and IV.13 for a 3.5 cm wide replica and measured g_a using heated leaf replicas. The conductances were calculated (i) assuming that free and forced convection could be treated as conductances in parallel, and (ii) using eq. IV.13 when $u = 0$ m s^{-1}, and eq. IV.12 for all other measurements (Monteith and Unsworth, 1990). Under laminar flow ($u < 2.5$ m s^{-1}), calculated values were similar to measured, with the Monteith and Unsworth calculation agreeing better than that calculated for parallel conductances. At high wind speeds ($u > 3.0$ m s^{-1}) air flow becomes more turbulent, so break down of laminar flow theory would be expected. 'Initially turbulent' flow produced higher conductances than the laminar flow, similar to the results of Dixon (1982) using the 'transient' method.

The relationship between Reynolds number ($\log_{10}$ Re), and Nusselt number ($\log_{10}$ Nu), where Re = (ud/ν), and Nu = (dg_a/D_h) (Figure IV.5), changed when Re > 8000, indicating a change from laminar to turbulent flow. The transition point was lower than quoted change to turbulent flow over flat plates of Re > 10^5, (Grace, 1983), but quite near that given by Monteith and Unsworth (1990) Re > 2 x 10^4, and may have resulted from turbulence generated by the frame holding the replicas, as was noted by Grace *et al.* (1980). The slope of the line of $\log_{10}$ Re vs $\log_{10}$ Nu for laminar flow was 0.51 with an intercept of 0.05, similar to prediction from laminar flow theory (slope of 0.5 and intercept of zero), (Dixon, 1982). As turbulent transfer occurred $u > 3$ m s^{-1} the slope of the line increased to 0.755. 'Initially turbulent' wind flow produced a linear relationship between $\log_{10}$ Re and $\log_{10}$ Nu over the range of wind speeds tested, with gradient of 0.68. Both these values are higher, than the comparable values found by Dixon (1982) using replicas of *Fagus sylvatica* leaves.

Figure IV.4 Conductances measured with heated leaf replica method, in 'initially turbulent' flow (▲), and 'initially laminar' flow (●). Conductances calculated from eq. IV.12 and IV.13 assuming parallel conductances (······) Monteith and Unsworth (—).



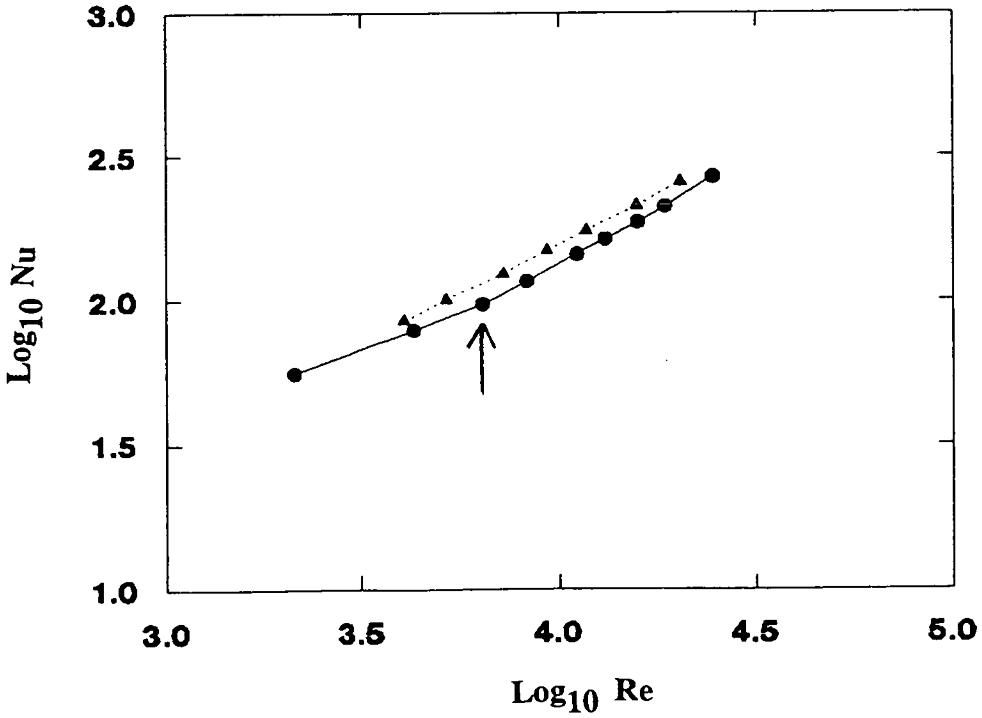


Figure IV.5 Relationship between $\log_{10}$ Nu and $\log_{10}$ Re, for heated leaf replicas in a wind tunnel, under 'initially turbulent' (▲), and 'initially laminar' (●) flow conditions. The arrow marks the change from laminar to turbulent flow, under 'initially laminar' flow conditions.

Blotting paper comparison

The heated replica method was compared against the wet blotting paper method in the wind tunnel. Boundary layer conductances estimated with the wetted blotting paper were lower than those estimated from the replicas with maximum differences of around 1 cm s^{-1}, (Figure IV.6). If conductances are corrected for free convection equation IV.13 the two lines become closer. Large errors associated with the blotting paper technique, and good agreement between the heated replicas and equations IV.12 and IV.13, suggested that heated leaf replica estimates may be nearer the actual g_a.

Discussion of assumptions

This technique is designed to give estimates of g_a for real leaves in the field. Leaf replicas do not behave exactly like real leaves for several reasons. They are fixed, horizontal, and do not flap in the wind. Neither leaf flapping or leaf curvature had significant effect on g_a, (Parlange *et al.*, 1971). Grace *et al.* (1980) and Parkhurst *et al.* (1968) found little influence of leaf angle on g_a, however at high Grashof numbers (large temperature gradients and low wind speeds) it may become important.

Pearman *et al.* (1972) found measured values of boundary layer conductances 1.5 times, and Parlange *et al.* (1971) 2.5 times, higher than expected from equation IV.12. The physical appearance of the replica may resemble the leaf ie. similar forced convection. However, air to leaf temperature differences and air to replica temperature differences may not be the same, and consequently free convection components will be different.

If the two conductances of free and forced convection are linked in parallel it would be possible to subtract the air to replica and add the air to leaf free convection component of conductance. In the case of the heated leaf replica, convection occurs from the upper and lower surfaces. Heat moves upwards, so the conductance of the lower surface may be lower than the upper surface. Equation IV.13 is for an upward facing surface. Kreith (1973) gives a factor of 0.5 for transfer from a downward facing surface, giving a combined conductance from two

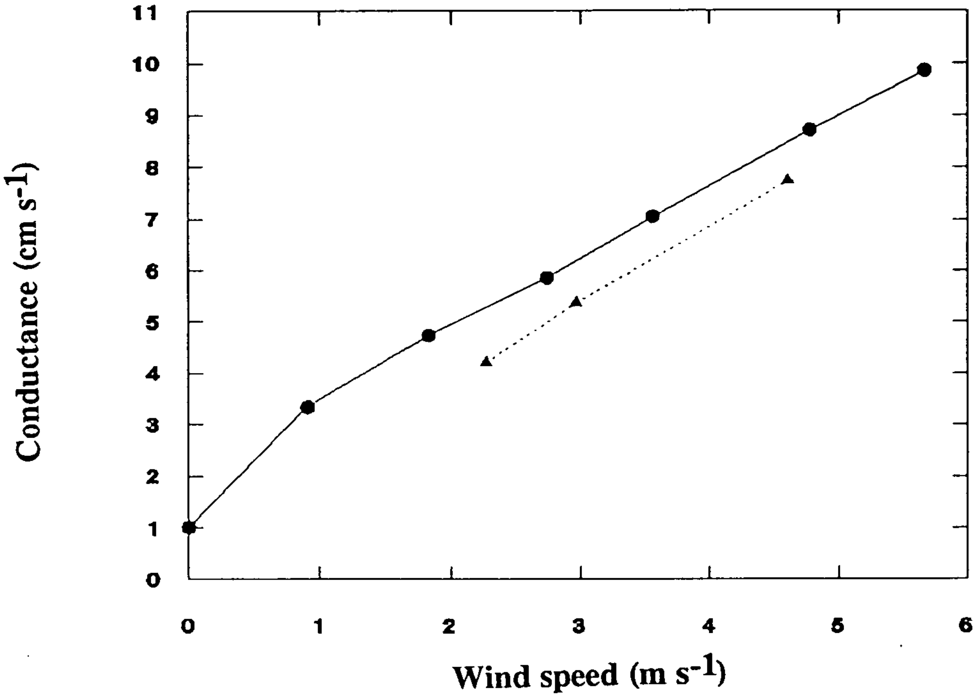


Figure IV.6 Comparison of boundary layer conductance measured using heated leaf replicas (●), and blotting paper replicas (▲), for 'initially laminar' flow conditions in a wind tunnel.

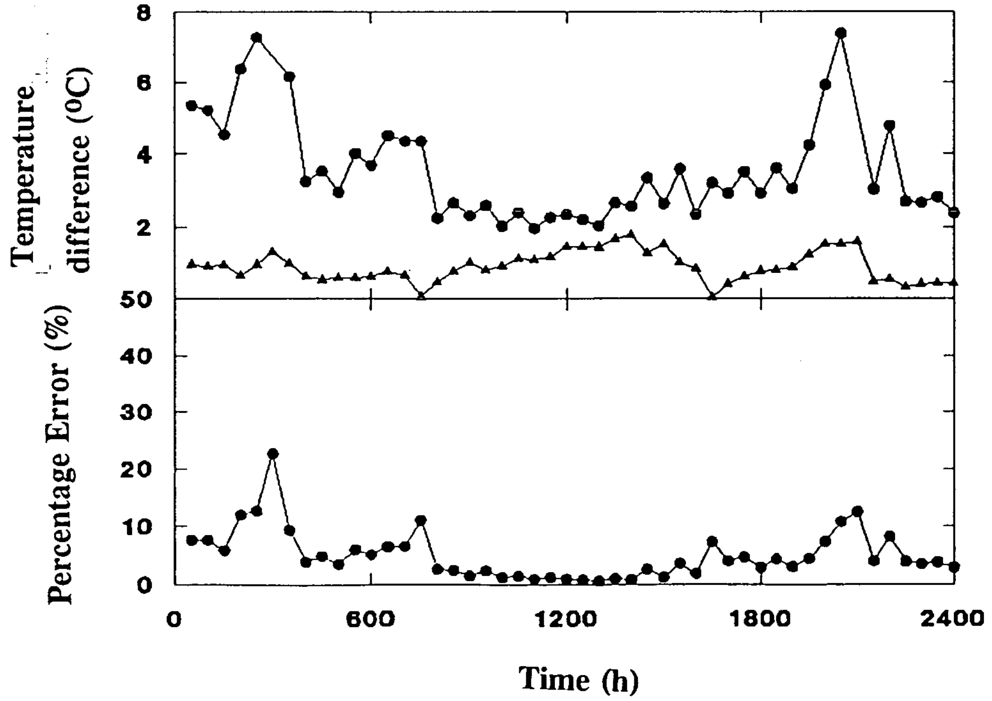


Figure IV.7 Diurnal pattern of a) leaf to air (▲), and replica to air (●) temperature differences. b) The calculated percentage error in g_a caused by measuring the replica to air as opposed to the leaf to air temperature differences.

sides of 1.5. Dixon and Grace (1983) showed that conductances of real leaves were twice those calculated from Equation IV.13. Using data for $u = 0$ m s^{-1} in the wind tunnel, a factor of two brought measured conductances within 0.07 cm s^{-1} of calculated values using equation IV.13. Applying this correction to field data did not have a large effect upon day time conductances (ca. 4 %), since convection was primarily forced. However at certain times of the day this correction changed measured g_a by up to 24 %, Figure IV.8.

Conclusion

The leaf replica method provided an easily constructed and logged system for measuring leaf boundary layer conductances under field conditions. Wind tunnel tests have shown that while laminar conditions exist the replica measurements agree with calculated values from engineering texts. Under turbulent conditions, the leaf replica may give better estimate of g_a than engineering equations.

The system outlined in this paper automatically records and switches between replicas, allowing for the correction for differences between plates. Corrections for differences in L_e between plates, and free convection components of g_a between replicas and real leaves can be calculated, but under most conditions are small.

Thus leaf replicas have potential in measuring g_a of plant leaves under turbulent conditions. Enabling calculation of heat and water vapour transfer from real leaves in the field, leading to increased understanding of the coupling of plants to their environment.

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APPENDIX V

NORMALIZED WIND SPEEDS AND TURBULENCE INTENSITIES* FOR 1989

Results of normalized wind speed and turbulence intensities are presented for time intervals and wind direction groups described in Table 4.1. Measurements were taken every 30 minutes for approximately two weeks in every time interval, ie. each time interval consisted of approximately 670 measurements. The % time column gives the % of time during that interval that the wind was coming from the direction under the Dir column. Standard errors were calculated from the pooled variance at the four distances.

Table V.1 Normalized wind speed interval A

Dir	1h	3h	6h	10h	s.e.	% time
30	1.323	1.500	1.578	1.568	0.129	1.7
90	0.808	1.083	0.907	1.133	0.109	0.3
150	0.937	1.078	1.058	1.118	0.027	7.0
190	0.540	0.645	0.716	0.772	0.011	12.4
210	0.724	0.644	0.555	0.669	0.006	25.1
225	0.863	0.748	0.585	0.709	0.014	15.2
235	0.940	0.782	0.644	0.756	0.022	11.3
245	1.124	0.841	0.661	0.840	0.032	11.0
255	1.146	0.836	0.629	0.820	0.008	6.6
265	1.277	0.884	0.643	0.865	0.011	4.0
275	1.178	1.143	0.601	0.845	0.041	1.4
285	1.099	0.768	0.594	0.806	0.011	1.9
295	0.879	0.446	0.657	0.826	0.025	0.7
305	0.833	0.676	0.618	0.765	0.015	0.9
315	0.811	0.000	0.687	0.823		0.2
330	0.675	0.682	0.650	0.803	0.039	0.2
350	0.441	0.762	0.843	0.944		0.2

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* NOTE TURBULENCE INTENSITIES REFERED TO IN THIS APPENDIX ARE THE SAME AS WIND VARIABILITIES REFERED TO IN CHAPTER IV.

Table V.2 Normalized wind speed interval B

Dir	1h	3h	6h	10h	s.e.	% time
30	1.079	1.121	1.351	1.151	0.018	4.0
90	1.220	1.298	1.464	1.285	0.013	2.7
150	1.014	1.141	1.176	1.109	0.033	5.0
190	0.785	0.834	0.872	0.846	0.028	4.2
210	0.689	0.599	0.665	0.654	0.008	8.5
225	0.875	0.613	0.694	0.722	0.027	9.5
235	0.931	0.595	0.635	0.685	0.013	12.2
245	1.195	0.710	0.748	0.817	0.035	18.2
255	1.290	0.669	0.599	0.806	0.013	13.7
265	1.471	0.909	0.747	0.954	0.037	10.7
275	1.260	0.709	0.547	0.805	0.026	4.2
285	1.231	0.783	0.769	0.930	0.048	3.2
295	0.725	0.699	0.806	0.895	0.094	0.5
305	0.802	0.665	0.748	0.861	0.061	1.0
315	0.738	0.438	0.638	0.727		0.2
330	0.507	0.579	0.742	0.632	0.032	1.0
350	0.654	0.696	0.890	0.811	0.030	1.0

Table V.3 Normalized wind speed interval C

Dir	1h	3h	6h	10h	s.e.	% time
30	1.036	1.144	1.223	1.074	0.020	2.2
90	1.583	1.734	1.631	1.546	0.035	3.5
150	1.224	1.359	1.396	1.279	0.042	13.0
190	0.732	0.876	0.976	0.794	0.015	4.2
210	0.834	0.753	0.897	0.819	0.019	10.5
225	0.987	0.591	0.771	0.794	0.008	9.1
235	1.030	0.540	0.724	0.806	0.007	11.3
245	1.137	0.477	0.632	0.836	0.007	10.8
255	1.183	0.465	0.589	0.766	0.005	15.3
265	1.155	0.476	0.589	0.751	0.008	8.1
275	1.133	0.534	0.593	0.729	0.010	5.9
285	1.104	0.510	0.555	0.701	0.017	2.0
295	0.957	0.504	0.570	0.724	0.015	2.0
305	0.868	0.612	0.669	0.731	0.023	1.5
315	0.839	0.000	0.000	0.000		0.2
330	0.708	0.750	0.803	0.692	0.056	0.2
350	0.528	0.690	0.995	0.864		0.2

Table V.4 Normalized wind speed interval D

Dir	1h	3h	6h	10h	s.e.	% time
30	0.979	1.390	1.292	1.044	0.054	3.3
90	1.478	1.533	1.421	1.352	0.055	4.1
150	1.069	1.290	1.194	1.092	0.022	18.6
190	0.711	0.891	0.919	0.819	0.015	10.0
210	0.639	0.700	0.805	0.792	0.016	6.7
225	0.784	0.503	0.777	0.817	0.011	9.3
235	0.853	0.521	0.729	0.794	0.013	11.9
245	0.931	0.489	0.681	0.806	0.018	10.0
255	1.065	0.383	0.606	0.780	0.021	6.7
265	1.046	0.368	0.572	0.724	0.020	4.5
275	0.952	0.360	0.506	0.703	0.027	1.1
285	0.836	0.402	0.615	0.769	0.007	2.6
295	0.744	0.442	0.722	0.737	0.019	3.0
305	1.042	0.588	1.122	0.797	0.066	2.6
315	0.914	0.967	1.162	0.789	0.077	2.6
330	0.862	0.685	0.928	0.816	0.053	0.7
350	0.642	1.287	1.356	1.020	0.098	2.2

Table V.5 Normalized wind speed interval E

Dir	1h	3h	6h	10h	s.e.	% time
30	0.861	1.263	0.999	1.040	0.038	1.0
90	1.243	1.490	1.198	1.330	0.052	3.6
150	0.927	1.098	0.895	0.941	0.019	14.3
190	0.683	1.013	1.191	0.902	0.024	15.3
210	0.917	0.696	0.975	0.801	0.052	9.2
225	0.976	0.615	0.838	0.752	0.070	7.7
235	0.755	0.577	0.767	0.718	0.018	8.7
245	0.779	0.599	0.698	0.712	0.018	11.2
255	0.824	0.725	0.723	0.740	0.025	13.3
265	0.850	0.628	0.852	0.849	0.031	5.1
275	0.993	0.661	0.825	0.802	0.056	3.1
285	0.856	0.623	0.887	0.902	0.042	4.6
295	1.057	0.777	0.828	0.745	0.100	2.0
305	0.816	0.823	0.929	0.894	0.054	1.0
315						0.0
330						0.0
350						0.0

Table V.6 Normalized wind speed interval F

Dir	1h	3h	6h	10h	s.e.	% time
30	1.451	1.438	1.826	1.547	0.066	4.4
90	2.214	2.394	2.326	2.251	0.022	30.4
150	1.471	1.584	1.655	1.474	0.025	27.6
190	0.867	1.213	1.614	1.138	0.032	6.8
210	0.659	0.805	1.385	1.046	0.040	2.4
225	0.597	0.742	1.204	0.989	0.049	1.7
235	0.708	0.404	1.188	0.993	0.026	2.4
245	0.865	0.511	1.014	1.030	0.019	4.1
255	0.984	0.377	0.943	0.977	0.031	6.5
265	0.825	0.527	0.874	0.921	0.020	6.8
275	0.740	0.000	0.938	0.928	0.023	4.1
285	0.705	0.000	1.146	1.040	0.059	1.0
295	0.538	0.000	1.004	1.055	0.034	0.7
305	0.773	0.000	1.409	1.055		0.3
315	0.891	0.977	1.510	1.302		0.3
330						0.0
350	0.755	0.879	1.355	1.075	0.141	0.3

Table V.7 Normalized turbulence intensity Interval A

Dir	1h	3h	6h	10h	s.e.	% time
30	0.912	0.866	0.837	0.748	0.061	1.7
90	1.164	1.335	1.286	1.358	0.170	0.3
150	1.165	1.032	0.965	0.886	0.029	7.7
190	1.835	1.751	1.530	1.313	0.034	14.1
210	1.199	1.400	1.535	1.249	0.019	25.8
225	0.979	1.005	1.424	1.188	0.017	15.3
235	0.912	0.902	1.172	1.066	0.020	11.8
245	0.830	0.801	1.043	0.926	0.015	11.1
255	0.750	0.763	0.963	0.836	0.014	6.6
265	0.737	0.776	0.902	0.822	0.020	4.0
275	0.883	0.576	1.024	0.895	0.048	1.4
285	0.947	0.824	1.173	0.962	0.016	1.9
295	1.139	1.677	1.216	1.033	0.077	0.7
305	1.164	1.195	1.239	0.990	0.036	0.9
315	1.062	0.000	1.320	1.075		0.2
330	0.828	0.974	1.153	0.940	0.090	0.3
350	1.971	0.828	0.847	0.738		0.2

Table V.8 Normalized turbulence intensity Interval B

Dir	1h	3h	6h	10h	s.e.	% time
30	0.981	0.964	0.947	1.063	0.021	4.0
90	1.060	1.196	1.158	1.274	0.032	2.7
150	1.145	1.244	1.248	1.269	0.121	6.0
190	1.115	0.953	1.006	0.928	0.065	5.2
210	1.076	1.271	1.462	1.230	0.038	9.2
225	1.018	1.206	1.384	1.304	0.032	9.7
235	0.954	1.076	1.224	1.300	0.027	12.5
245	0.917	0.885	1.133	1.153	0.029	19.0
255	0.786	0.797	1.044	1.019	0.026	14.5
265	0.988	0.820	0.936	1.072	0.047	11.2
275	0.827	0.922	1.147	1.172	0.049	4.5
285	0.827	0.925	1.173	1.016	0.053	3.2
295	1.607	1.034	1.155	1.020	0.124	1.0
305	1.112	1.152	1.073	1.031	0.105	1.0
315	1.044	1.603	1.478	0.718	0.310	0.5
330	1.463	1.317	1.482	1.498	0.111	1.7
350	1.239	1.352	1.186	1.177	0.081	1.0

Table V.9 Normalized turbulence intensity Interval C

Dir	1h	3h	6h	10h	s.e.	% time
30	0.934	0.895	0.970	1.023	0.033	2.5
90	1.614	1.561	1.654	1.723	0.207	3.5
150	1.037	1.027	0.966	1.044	0.022	14.5
190	1.090	1.097	1.170	1.031	0.037	6.4
210	1.068	1.143	1.398	1.348	0.025	13.5
225	0.882	1.085	1.372	1.384	0.029	10.1
235	0.937	1.011	1.474	1.483	0.024	11.6
245	0.909	0.863	1.407	1.315	0.024	11.3
255	0.767	0.795	1.354	1.396	0.019	16.0
265	0.837	0.784	1.256	1.353	0.031	8.3
275	0.898	0.729	1.422	1.228	0.037	5.9
285	0.785	0.851	1.551	1.307	0.055	2.2
295	1.122	1.051	1.690	1.534	0.038	2.2
305	1.288	0.957	1.707	1.531	0.054	1.5
315	1.039	0.546	1.033	0.780	0.069	0.7
330	0.848	0.692	0.636	0.705	0.073	1.3
350	0.888	1.161	0.742	0.653	0.128	0.8

Table V.10 Normalized turbulence intensity Interval D

Dir	1h	3h	6h	10h	s.e.	% time
30	3.021	2.831	3.147	2.852	0.539	5.2
90	1.179	0.959	1.168	1.134	0.042	6.3
150	1.269	0.956	1.071	1.070	0.031	20.8
190	1.305	1.024	1.122	1.123	0.031	15.6
210	1.079	0.984	1.098	1.098	0.036	14.9
225	0.777	1.001	1.066	1.169	0.036	12.6
235	0.984	0.892	1.283	1.344	0.035	14.1
245	0.895	0.822	1.145	1.270	0.035	11.9
255	0.858	0.865	1.290	0.976	0.050	6.7
265	0.964	0.679	1.323	1.215	0.062	4.8
275	1.205	0.373	1.329	1.649	0.106	1.1
285	0.981	0.692	1.225	1.151	0.081	2.6
295	0.925	0.825	1.377	1.091	0.064	3.7
305	0.774	0.920	0.923	0.745	0.072	3.3
315	1.016	1.146	1.331	1.275	0.060	3.3
330	0.897	0.827	1.220	0.851	0.160	1.1
350	2.294	1.584	1.825	1.920	0.190	3.0

Table V.11 Normalized turbulence intensity Interval E

Dir	1h	3h	6h	10h	s.e.	% time
30	0.937	0.647	0.823	0.849	0.037	1.0
90	1.118	1.026	1.112	0.924	0.070	5.1
150	1.193	1.027	1.329	1.180	0.079	17.9
190	1.184	1.397	0.869	0.964	0.078	28.1
210	1.192	1.145	1.123	1.058	0.076	19.4
225	1.143	0.962	1.050	0.940	0.092	10.2
235	1.053	0.582	1.070	1.217	0.055	9.2
245	1.069	0.691	1.096	1.187	0.043	12.8
255	0.965	0.609	1.010	1.217	0.038	15.3
265	0.846	0.456	0.884	1.031	0.049	6.6
275	0.996	0.461	0.625	0.991	0.072	2.6
285	0.755	0.603	0.815	0.973	0.043	6.1
295	1.225	0.554	0.959	1.153	0.075	1.5
305	0.750	0.755	0.955	0.953	0.077	1.0
315	1.102	0.869	1.191	0.989		0.5
330						0.0
350						0.0

Table V.12 Normalized turbulence intensity Interval F

Dir	1h	3h	6h	10h	s.e.	% time
30	0.909	0.976	0.626	0.807	0.026	3.4
90	0.874	0.895	0.731	0.915	0.039	26.3
150	1.286	1.257	1.005	1.277	0.086	29.0
190	0.753	0.888	0.609	0.806	0.029	12.6
210	0.773	0.936	0.803	1.005	0.050	4.4
225	0.837	0.838	1.203	1.348	0.161	3.4
235	0.633	0.714	1.144	1.521	0.148	6.1
245	0.713	0.723	0.685	0.905	0.033	6.8
255	0.620	0.498	0.747	0.967	0.034	6.8
265	0.753	0.715	0.881	1.298	0.100	7.2
275	0.763	0.432	0.684	0.991	0.028	6.1
285	1.000	0.669	0.556	0.852	0.068	1.4
295	0.998	0.833	0.579	0.857	0.063	0.7
305	0.721	0.000	0.554	0.828		0.3
315	0.824	0.654	0.525	0.472	0.173	0.3
330						0.0
350	0.831	1.093	1.012	1.007	0.180	0.7