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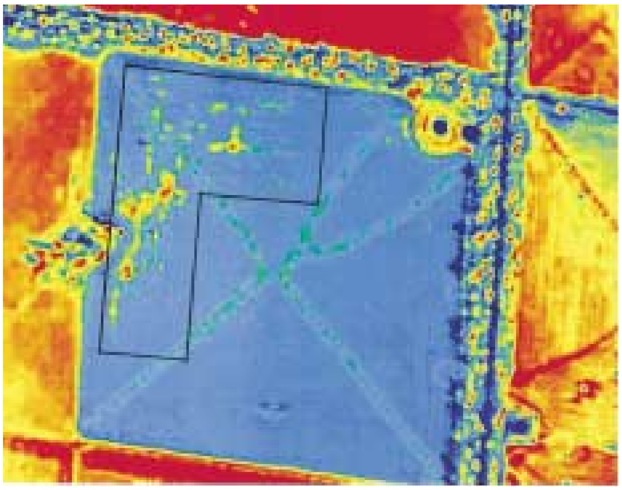

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# The Australian National Windbreaks Program: overview and summary of results

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*Abstract.* This overview paper presents a description of the National Windbreaks Program (NWP) — its objectives, the main methods used to achieve these objectives and a summary of the key results. It draws these from the individual papers appearing in this special issue, which provide detailed descriptions and discussion about the specific research sites and research methods used, in addition to interpreting and discussing the results. The key findings were the following:

(i) Two broad areas of crop and pasture response can be identified downwind of a porous windbreak: a zone of reduced yield associated with competition with the windbreak trees that extended from 1 H to 3 H, where H is the windbreak height, and a zone of unchanged or slightly increased yield stretching downwind to 10 H or 20 H.

(ii) Averaged over the paddock, yield gains due to the effect of shelter on microclimate were smaller than expected — especially for cereals. Yield simulations conducted using the APSIM model and 20 years of historical climate data confirmed this result for longer periods and for other crop growing regions in Australia. Larger yield gains were simulated at locations where the latter part of the growing season was characterised by high atmospheric demand and a depleted soil water store.

(iii) Economic analyses that account for the costs of establishing windbreaks, losses due to competition and yield gains as a result of shelter found that windbreaks will either lead to a small financial gain or be cost neutral.

(iv) Part of the reason for the relatively small changes in yield measured at the field sites was the variable wind climate which meant that the crop was only sheltered for a small proportion of the growing season. In much of southern Australia, where the day-to-day and seasonal variability in wind direction is large, additional windbreaks planted around the paddock perimeter or as closely-spaced rows within the paddock will be needed to provide more consistent levels of shelter.

(v) Protection from infrequent, high magnitude wind events that cause plant damage and soil erosion was observed to lead to the largest yield gains. The main forms of direct damage were sandblasting, which either buries or removes seedlings from the soil or damages the leaves and stems, and direct leaf tearing and stripping.

(vi) A corollary to these findings is the differing effect that porous windbreaks have on the air temperature and humidity compared to wind. While winds are reduced in strength in a zone that extends from 5 H upwind to at least 25 H downwind of the windbreak, the effects of shelter on temperature and humidity are smaller and restricted mainly to the quiet zone. This means that fewer windbreaks are required to achieve reductions in wind damage than for altering the microclimate.

(vii) The wind tunnel experiments illustrate the important aspects of windbreak structure that determine the airflow downwind, and subsequent microclimate changes, in winds oriented both perpendicular and obliquely to porous windbreaks. These results enable a series of guidelines to be forwarded for designing windbreaks for Australian agricultural systems.

*Additional keywords:* windbreaks, shelter, agricultural productivity, microclimates, water use.

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## Introduction

### *Why a National Windbreaks Program in Australia?*

The National Windbreaks Program (NWP) was initiated in 1993 in response to the growing recognition of the potential role for trees in reducing land degradation in Australia's rural landscape, especially from wind erosion, waterlogging, and dryland salinity (Bird *et al*. 1992; Prinsley 1992). At the same time research, mostly from overseas, had shown that shelter provided by tree windbreaks can increase agricultural productivity (see reviews by Nuberg 1998; Bird 1998; Brandle *et al*. 1988) sufficiently to compensate for the costs associated with establishment. This raised the possibility that tree windbreaks could provide a way to incorporate trees into farms — bringing both environmental and economic benefits to the agricultural enterprise. Tree windbreaks can confer multiple benefits (Abel *et al*. 1997). They provide shade and shelter for growing crops, pasture and livestock; yield timber and fodder to supplement farm income and stock feed; add biodiversity to the landscape and improve its aesthetic value and ameliorate local waterlogging and recharge. At this time, only 2 studies had investigated the impact of shelter from tree windbreaks on crop productivity in Australia (Bicknell 1991; Burke 1991) (see later section under 'Past research').

An assessment of whether tree windbreaks can realise at least some of these potential benefits, specifically the effects of windbreaks on crop and pasture productivity, requires quantifying their environmental and productivity effects. This task is complicated by the interactive and complex nature of the key mechanisms at play. In summary, these are: (i) the effect of trees on airflow; (ii) the consequent effects on temperature, humidity and the associated water, heat and $CO_2$ fluxes; (iii) the competition for resources (water, light and nutrients) between the trees and the crop or pasture; (iv) the effect of wind shelter in suppressing wind erosion; (v) the implications of these 4 factors for plant growth and crop productivity; and (vi) similar implications for animal productivity. The magnitude and relative importance of these mechanisms vary with climate, soil type and farming practice, which undermines a simple extrapolation of results found at 1 site.

Clearly, to assess the benefits and costs, and plan tree windbreaks that are effective in environmental, agronomic and economic terms, it was necessary to take an integrated view and to develop a predictive capability. The NWP was a coordinated research effort that provided the opportunity to adopt this integrated approach. Its aim was to develop a quantitative understanding of the interaction between windbreaks, microclimate and crop and pasture growth through a combination of field measurements, wind tunnel simulations, intensive micrometeorological observations and simulation modelling. The purpose of this paper is to describe the aims and objectives of the NWP, the research methods used, and a summary of the key results. First, we describe the main mechanisms by which wind shelter can modify microclimates and plant growth and review the evidence for windbreak effects on agricultural productivity with a focus on Australian agriculture.

### *Windbreak mechanisms*

A tree windbreak provides shelter from the wind and so alters the mean wind speed, wind direction and turbulence of the airflow. Cleugh (1998), McNaughton (1988) and others provide detailed explanations of how windbreaks modify airflow, microclimates and thence crop and pasture growth. The main mechanisms by which agricultural productivity can be modified are the following:

(i) Windbreaks provide shelter from the wind, which in turn reduces the direct mechanical effects of wind including wind erosion, which leads to sandblasting, burial and/or exposure of seeds and seedlings and stripping of nutrients; and plant damage such as leaf tearing and removal, damage to fruit and plant lodging.

(ii) Windbreaks alter the microclimate by providing shade from direct solar radiation and by trapping long-wave radiation. By altering the airflow, the turbulent exchanges of heat, water vapour and $CO_2$ are also modified and thence the temperature and humidity.

(iii) Windbreaks alter the flow of water and nutrients by competing with the surrounding plants in the narrow interface zone; changing the partitioning between soil and plant evaporation microclimate; and by modifying the water-use efficiency of the plants.

(iv) Windbreaks affect the ecology of the windbreak–crop–soil system in 2 ways. First, the environment for pests and pathogens is altered as a result of microclimate changes and altering the airflow affects the transport pathways for pests, pathogens, pollen, and pollutants. Second, adding a vegetated windbreak alters the biodiversity and creates opportunities for both competition and complementarity between components of the system. Animal behaviour will also be modified by the addition of a windbreak.

Some of these mechanisms operate incrementally over time while some occur only intermittently — although their impact can be catastrophic. Protection from low frequency, large magnitude weather events, such as crop lodging in a severe storm, is an intermittent windbreak effect. Sheltered soils that are warmer by day, and lose less moisture through evaporation, can encourage earlier germination, plant growth and improve water use efficiency. This latter example illustrates a potential incremental effect of a windbreak that operates over the entire growing season. Economic benefits may flow in both examples, but the timing, magnitudes and reliability differ.

### *Effects of shelter on agricultural productivity in Australia*

*Limits to productivity.* The principal crops grown in Australia are cereals — both 'winter' (autumn–winter–

spring) and 'summer' (spring–summer–autumn). Rice, maize and sorghum comprise most of the summer cereals while wheat, oats and barley, often grown in rotation with either a pasture or more recently canola, field peas and lucerne, make up the winter cereals. Other crops of consequence are cotton, generally grown under irrigation in summer, and sugarcane on the coastal fringe of tropical Australia. Wheat is still the largest crop in terms of area planted, production and gross value (Australian Bureau of Statistics 1999). It, along with the other cereals, is grown in a large crescent-shaped region that extends from the western and southern parts of Western Australia through South Australia, Victoria, and into central Queensland.

This wheat-growing region, which is mostly rain-fed (only 1.6% of Australia's cropping area is irrigated), extends across a wide range of climatic regimes. To quote from Nuberg (1998), 'Australia's rainfed cropping systems exist in a belt that stretches across a Mediterranean climate with hot dry summers and cool, wet winters with 250–600 mm annual rainfall; a dry temperate climate with seasonally uniform rainfall distribution (400–650 mm); and a subtropical climate with summer dominant rainfall (450–1000 mm)'. In this climatic region, temperature and light are seldom the factors limiting productivity (with the exception of some winter frost-prone regions of north-eastern Victoria and New South Wales, and southern Western Australia). While this cropping region has a moderate to high average 'winter moisture index' (Parkinson 1986), which is the ratio of actual to potential evaporation and is thus an index to surplus moisture, it is also a region associated with moderate to high levels of rainfall variability (Fig. 1). The main climatic factor that limits productivity in much of Australia's cropping region is thus soil moisture — the balance between rainfall and evaporation. Soil fertility, which is moderate to low in much of this region, also limits productivity (Nuberg 1998).

This brief analysis suggests that a shelter mechanism with the greatest impact on crop productivity in Australia would be one that led to reduced evaporation fluxes and hence conserved soil water and lessened stress to the plant from high evaporative demand. Amelioration of low winter temperatures in some of the upland areas in south-east Australia used for grazing and pasture production, is another potential benefit of shelter, in addition to a reduction in direct damage.

*Past research.* As discussed in Prinsley (1992), and more recently in Nuberg (1998) and Bird (1998), there has been surprisingly little research investigating windbreak effects

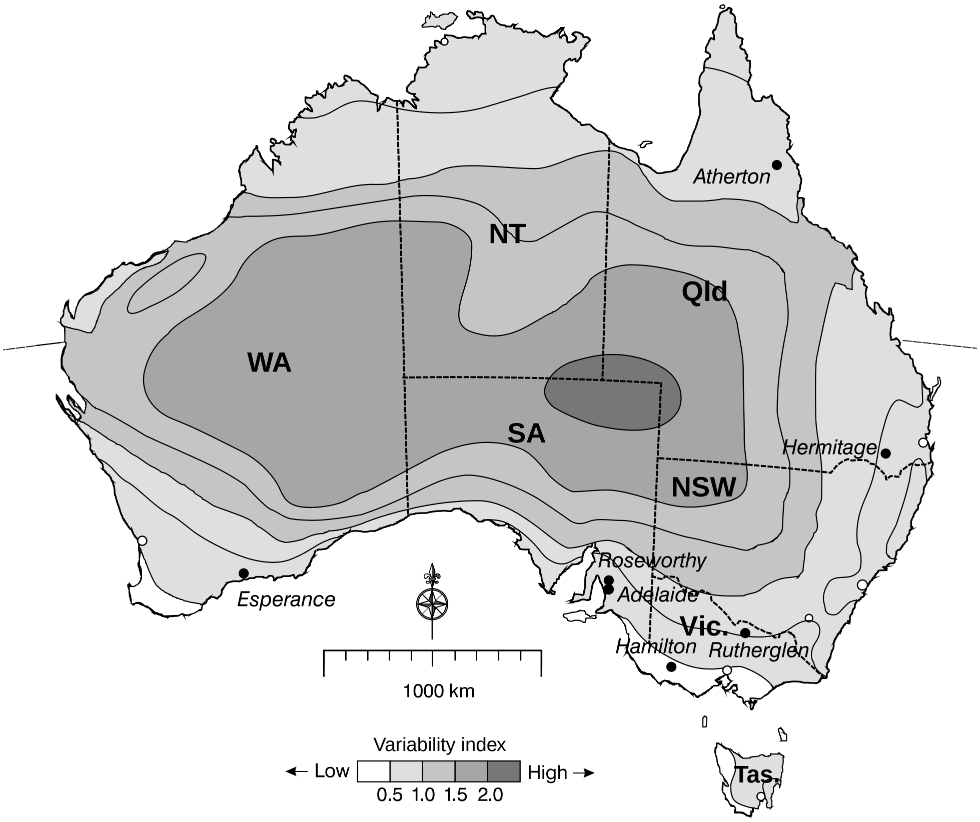

**Figure 1.** Rainfall variability across Australia and the field windbreak sites used in the National Windbreaks Program. The rainfall variability is taken from the Bureau of Meteorology's 1 : 20 000 000 map (1981). The variability index shown in this figure is calculated from the rainfall statistics measured at sites that have more than 30 years of record, as: (90th percentile – 10th percentile)/50th percentile.

on crop and pasture productivity in Australia. Discussions that culminated in the launch of the National Windbreaks Program were sparked by the promising results from the studies of Burke (1991) and Bicknell (1991). These 2 studies seem to be the only investigations into the effects of windbreak shelter on crop yields in Australia, although earlier studies by Lynch and Marshall (1969) demonstrated improved animal productivity, apparently as a result of the benefits of shelter on pasture production.

Burke (1991) investigated the effect of tree windbreaks on wheat and oat yields around E–W and N–S oriented tree windbreaks in Victoria over a single cropping season. He found wheat yield gains of 20 and 25% in the sheltered zone extending from about 1.5 H to 9 H (where H is the windbreak height) downwind of the N–S and E–W windbreaks. Yield gains in the oat crop were even larger (47%) in the sheltered zone leeward of the E–W oriented windbreak, but negligible behind the N–S windbreak. Bicknell (1991) studied lupin grain yields in the lee of windbreaks in Western Australia. While his results have been reported as showing 27–30% yield gains for lupins (Nuberg 1998), the open field yield was based on a single data point at 20 H leeward of the windbreak in the 1988 crop year and 14 H in the 1989 crop year. Given the typical variability of yields in field crops, it is not clear that this baseline 'open field' yield was adequately defined. Furthermore, factors such as soil variability, waterlogging and the nature of the seasonal climate need investigation before this yield response can be solely attributed to a windbreak effect.

Despite these concerns, the magnitude of these yield gains was similar to some of the more positive results from North America and Europe (see reviews by Kort 1988 and Nuberg 1998) and so provided the incentive for the Australian community to conduct further research to quantify the potential microclimate and yield benefits to flow from tree windbreaks.

As Nuberg's review at the inception of the National Windbreaks Program noted, research is needed to understand the mechanisms that contribute to shelter effects in Australian cropping systems (Nuberg 1998). There are some aspects of Australia's climate that make it different from overseas locations where much of the windbreak research has been conducted and so their results cannot be assumed, *a priori*, to apply in Australia. First, windbreaks in the colder regions of both North America and Northern Europe trap winter snow, which provides an important moisture source for spring-planted crops. Second, Australia's wind climate is quite different to some of the regions where windbreak benefits have been observed. For example, New Zealand is located in the mid-latitude westerly belt which leads to a more consistent wind direction and much stronger wind speeds than typically observed in Australia. Third, the seasonal change in wind direction, and associated weather — e.g. cool south-westerlies in winter and hot, dry north-westerlies in spring and summer — may be of critical importance in limiting agricultural productivity in Australia. Finally, rainfall variability in the Australian rainfed cropping regions is amongst the highest in the world, and especially will be higher than many parts of northern Europe and North America (although the latter features will be shared with the central and southern portions of the Great Plains in the US, where protection from hot, dry winds is also seen to be an important benefit of windbreaks).

Bird's review (Bird 1998) concluded that there was also a surprising lack of information on the role of shelter in improving pasture production. He identified several conflicting results, and the possibility that nutrient transfer may play a larger role than previously considered in results showing improved pasture yields in the sheltered zone behind windbreaks. He also points out the methodological difficulties associated with showing a shelter effect in grazed pasture.

These conclusions were instrumental in directing the final approach taken in the National Windbreaks Program.

### *National Windbreaks Program — objectives and hypothesis*

The NWP aimed to provide an integrated and quantitative assessment of the response of agricultural systems to windbreaks. Its specific objectives were to: (i) quantify windbreak effects on the microclimate and plant growth of adjacent crops and pastures through field measurements, wind tunnel simulations, and environmental and crop modelling; (ii) develop a predictive capacity to generalise windbreak effects and optimise windbreak use.

The NWP initially focused on the role of microclimate changes in altering soil water use, crop and pasture growth and final yields, i.e. the second and third of the mechanisms listed previously. However, the potential impact of a reduction in direct damage on yields, i.e. the first mechanism, became apparent early in the NWP and was thus incorporated as a secondary focus. These foci are reflected in the program's central hypothesis (from 1st NWP meeting in Kuranda, February 1994): 'Windbreaks increase plant development, yield and quality primarily by their effects on the plant water and energy budgets and secondarily on the incidence of abrasion, canopy damage and the ecology of pests, diseases and weeds.'

Individual research groups within the NWP had additional research objectives, as they describe in the papers that follow this overview.

## Overview of research methods

Achieving the NWP objectives required an integrated research methodology, combining field measurements, detailed experiments and numerical modelling. The details of the methods used by each group are described in their papers (Bird *et al.* 2002*a*, 2002*b*, A. J. Snell and S. J. Brooks pers. comm.; Sudmeyer and Scott 2002*a*; Nuberg *et al.* 2002), while this section summarises the main methodological aspects.

### *Field measurements*

Field measurements were obtained over 4 growing seasons between 1994 and 1997, in pasture, grain and horticultural crops sheltered by

**Table 1. Detail of sites, crops and research groups**

| Year and location | Field windbreaks | | | | Artificial shelters | | |
|---|---|---|---|---|---|---|---|
| | 1994 | 1995 | 1996 | 1997 | 1995 | 1996 | 1997 |
| Esperance (33°50′S, 121°53′E)<br>(WA Department of Agriculture) | Lupins | Canola | Barley | Lupins | Lupins | Wheat | Wheat |
| Roseworthy (34°33′S, 138°42′E)<br>(Roseworthy Agricultural College) | Wheat, canola and faba beans in rotation | | | | — | Wheat | Wheat |
| Rutherglen (36°7′S, 146°31′E)<br>(Victoria Department of Agriculture) | Lupins | Wheat | — | — | — | Wheat | Wheat |
| Hamilton (37°30′S, 141°55′E)<br>(Victoria Department of Agriculture) | Grazed perennial pasture | | | | —<br>— | Perennial pasture | Perennial pasture |
| Warwick (28°37′S, 151°57′E)<br>(APSRU) | — | — | — | — | — | Mungbeans<br>— | Irrigated wheat, mungbeans |
| Atherton (17°13′S, 145°34′E)<br>(Department of Primary Industries Qld) | Maize and potatoes in rotation | | | | — | | |

tree windbreaks which were oriented to protect paddocks from the predominant wind directions over the growing season. The details of windbreak orientation, dimensions, porosity and species are provided in each of the research groups' papers. These windbreak sites represent a cross-section of the climate and soil regimes that characterise the cereal and grazing areas of southern Australia. A site established on the Atherton Tablelands in Far North Queensland enabled an assessment of windbreak effects on a horticultural crop, as well as a cereal, in a tropical climate. The site locations are illustrated in Figure 1, while Table 1 provides a detailed summary of the crops grown at each site and the agency that undertook the research.

At each of the field sites listed in Table 1, a common core measurement protocol was adopted. The fundamental horizontal distance used throughout the NWP was the windbreak height (H), measured as the distance, in multiples of windbreak heights, from the trunk of the outer tree row. Measurement transects, oriented normal (i.e. at right angles) to the tree windbreak were established at each field site. Where a prevailing wind direction was expected, at least over the growing season, these transects extended to a distance of at least 20 H on the leeward or downwind side of the windbreak. A series of at least 6 measurement stations were selected at various downwind distances, from about 1 H to >20 H, along these transects. To increase the sample size, 3 separate transects were typically established, running parallel to each other and oriented at right angles to the windbreak. Figure 2 is a schematic showing this typical layout, but the number of measurement stations shown is indicative only. The reader is referred to the individual research papers for a description of the actual layout for each site.

The following were measured at each of the stations according to a commonly agreed data acquisition protocol: (i) crop and pasture growth rates (leaf area index, canopy height, biomass and final yields) and phenology; (ii) soil water changes; (iii) damage assessments, where appropriate.

Soil water was monitored at all sites using neutron moisture meters, while a combination of machine and hand-harvesting methods were used to determine biomass and yields. Details of the methods used, including calibrations, are provided in the individual papers that follow this overview. An automatic weather station was located at a reference location, either 20 H upwind or >20 H downwind of the windbreak, to provide measurements of the meteorology at a location assumed to be unaffected by the windbreak. [A few sites used a reference station at 20 H downwind (see individual papers in this volume) because an upwind position was not available. While the windbreak will still influence the airflow at this position, its influence on the other microclimate parameters, such as temperature and humidity, will be

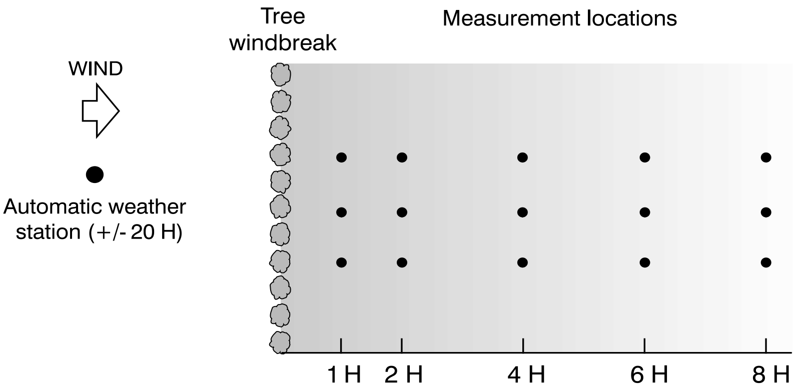

**Figure 2.** Typical measurement layout at each of the tree windbreak field sites. Rainfall, humidity, windspeed and direction, soil and air temperature and solar radiation were measured at the automatic weather station. Soil water, biomass, leaf area index, crop height and final yield were measured at each sampling location (●).

minimal.] All stations used the same set of sensors positioned at similar heights relative to the underlying plant canopy or soil surface. A 10 s sampling interval was used for all measurements, and 15 min averages calculated and stored on Data Electronics loggers (Model Datataker 50). A calibration weather station was developed for the NWP, and circulated to each of the field sites for intercomparison at least once during the experimental program.

Following a detailed literature survey (Miller *et al.* 1995; Cleugh *et al.* 1998), the potential for direct wind damage to limit crop production was realised and this mechanism became a secondary focus of the NWP. A sampling strategy (see Appendix 1) and a ranking system were devised to assess levels of damage should a wind damage event occur. Snell and Brooks (2002) detail the particular methods used to quantify the level of damage observed in their maize and potato crops. In addition to these intensive measurements at a single site, a survey of yields at more than 50 windbreak sites was conducted, as described by Sudmeyer *et al*. (2001*a*) for Western Australia.

### *Experiments*

While these field measurements provided invaluable insight into how tree windbreaks interact with crops in a field situation, quantifying some of the mechanisms required more detailed experimental investigation.

The CSIRO Land and Water (Pye Laboratory) wind tunnel was used to conduct measurements of airflow and microclimates around model windbreaks. In these experiments, Cleugh and Hughes (2002) investigated the effects of windbreak length, height, orientation and porosity, and multiple windbreaks on airflow, scalar (heat and water vapour) fluxes and microclimate. A complementary field experiment was also conducted to, firstly, validate the applicability of these wind tunnel results to field situations and, secondly, to explore the effects of windbreaks on the diurnal variation of microclimate, especially atmospheric demand, and the effects of tree windbreak structure and orientation (Cleugh 2002*a*).

The variable nature of much of southern Australia's wind climate meant that consistent levels of shelter were absent at some of the field windbreak sites. To provide measurements of crop and pasture responses to constant shelter, research groups at the Rutherglen, Hamilton, Roseworthy and Esperance sites (Table 1) constructed square 'artificial' shelters from shade cloth. Most of the groups used shade cloth with 30% optical porosity, leading to about a 70% reduction in windspeed over the growing season. These shelters were 1 m in height and 10 m on the side, so samples taken in the middle of these enclosures were ≤5 H from the sheltering wall. The artificial shelters were replicated at each individual site, and constructed using a common design protocol to enable comparisons between sites. This design took into consideration the need to eliminate confounding effects such as shading or self-sheltering of each enclosure. The same suite of plant and soil measurements used at the field windbreak sites were made within and outside the shelters. In addition, measurements of temperature and relative humidity were conducted, just above canopy height, within and outside the shelters using Vaisala 50Y Humitter sensors placed in ventilated radiation shields. A further description of the methods used in, and results from, these artificial shelter experiments are described in Bird *et al.* (2002*b*) and Sudmeyer *et al.* (2002*b*).

### *Modelling*

The final component of the research methodology was the development and implementation of models — to interpret and generalise the results and to provide a predictive capability. The main modelling approaches included:

*Numerical airflow and scalar flux modelling*. Large Eddy Simulation models were used to simulate the airflow and scalar fluxes (Patton *et al*. 1998) around the porous windbreaks used in the wind tunnel experiments.

*SCAM* (*Soil–Canopy–Atmosphere Model*). SCAM is a 1-dimensional, biophysical model that simulates energy and water fluxes between the soil, plant canopy and atmosphere. It uses a state-of-the-art parameterisation of within and above canopy turbulence, radiation and soil water flows but does not simulate crop growth and yield. It was used to determine the sensitivity of canopy water and energy balances to shelter (Cleugh 2002*b*) and to provide calibrations of APSIM — the model used to simulate crop growth and yields.

*Crop growth simulations using APSIM*. The philosophy and architecture of APSIM (Agricultural Production Systems Simulator) are detailed in Meinke *et al*. (2002). APSIM was used to predict crop growth and final yields for the field sites (Esperance barley, Roseworthy wheat, Atherton maize) and artificial shelters (Esperance wheat, Rutherglen wheat and Warwick wheat and mung bean). In addition, APSIM was used to quantify the potential yield gains from shelter, and cost-benefit analyses, for selected agricultural regions of Australia (see Carberry *et al*. 2002).

## Key results

### *Windfield around a porous windbreak*

The wind tunnel and field results support the conceptual model of airflow around a porous windbreak pictured in Figure 3 (simplified from Cleugh and Hughes 2002). These data showed the presence of quiet and wake zones, and a turbulent mixing layer that is initiated at the top of the windbreak and grows with increasing distance downwind. These results showed that the main factors determining the amount and extent of wind shelter are:

*Porosity* (β). This determines the degree of shelter, i.e. the reduction in wind speed created by the windbreak. Table 1 in Cleugh and Hughes (2002) presents relationships between β and wind-speed reduction for artificial windbreaks constructed of mesh.

*Windbreak height* (H). This determines the distance over which wind speeds are reduced. This distance typically extends from –5 to +30 H (where negative and positive signs denote 'upwind' and 'downwind', respectively).

Figure 3 also illustrates the combined effect of porosity on the amount of wind shelter and windbreak height on the downwind extent of shelter, for the 3 windbreaks (low, medium and high porosity) used in the wind tunnel experiments described in Cleugh and Hughes (2002).

The wind tunnel and field measurements also found that the location downwind of a windbreak, where the maximum shelter and minimum windspeed occur, depends on the wind direction, the surrounding terrain and the windbreak height. For the range in windbreak porosities used in the wind tunnel experiments (30–70%), the porosity of the windbreak did not have a discernible effect on where the minimum wind speed occurs. This result is consistent with other findings in the literature (Cleugh 1998). For example, the modelling study of Wang and Takle (1997) showed that the shift in the minimum wind speed location with decreasing porosity was only well defined for a very low porosity windbreak (β = 10%).

These results have important implications for designing and managing windbreaks. Because the area of a paddock that is sheltered depends mostly on the height of the windbreak, rapid achievement of maximum tree height is advantageous. So, fast-growing tree species make good windbreaks as long as their fast-growing attributes do not compromise their porosity (see below). Another way to maximise windbreak height is to place the windbreak on a mound or ridge — the potential increase in both shelter amount and extent is illustrated by the experimental results described in Cleugh and Hughes (2002). Maximising the sheltered area, by manipulating windbreak height, is probably most important in broadacre cropping applications where farmers want to reduce the area set aside for the windbreak while maximising the area of the paddock that receives wind shelter.

Porosity is the factor that will determine the reduction in wind speed achieved through the use of a windbreak. A rough guide is that the windspeed reduction is similar to the windbreak density (1 – β), i.e. a porosity of 30% equates roughly to a 70% reduction in wind speed at the most sheltered location. Cleugh and Hughes (2002) provide more accurate relationships between wind speed reduction and porosity.

An optimum porosity will depend on the particular agricultural application, e.g. protecting stock or high value crops from wind damage may require the large reductions in wind speed that can be achieved using very dense windbreaks (β≤30%). On the other hand, even a porous windbreak (β = ~70%) creates a sheltered zone with similar dimensions to windbreaks with lower porosities. In fact, a most important result from the wind tunnel and field experiments was that the size of the sheltered quiet zone was independent of porosity for porous screens whose porosity ranged from 30 to 70%. This supports the view forwarded by Cleugh (1998) that the link between porosity and sheltered area has probably been exaggerated in much of the earlier literature. Thus, windbreaks with porosities as low as 30% do not reduce the downwind extent of the sheltered area as is commonly believed. Of course, very dense windbreaks with porosities well below 20% may have smaller sheltered zones (Wang and Takle 1987).

Indeed, managing the windbreak to achieve a uniform porosity along the windbreak's length or an optimum gradient in porosity over its height may be of greater importance than striving to achieve some optimum porosity. Measurements both in the field (Sudmeyer and Scott 2002*a*) and in the wind tunnel reveal the presence of accelerating flow through windbreak gaps which increase the possibility of wind erosion and thus direct damage to plants growing in the near windbreak zone. Other studies have shown how changes in porosity with height can modify the flow (e.g. Wilson 1987), which is useful in applications such as using windbreaks to control snow accumulation.

The reductions in windspeed, and the consequent changes in temperature and humidity (see below), are proportional to windbreak porosity and so the microclimate changes downwind of a very dense windbreak will be larger than for very porous windbreaks. Nonetheless, even a windbreak with the very high porosity of 70% reduces the near-surface wind speed by up to 30%. While such a reduction may lead to negligible changes in temperature and humidity (Cleugh

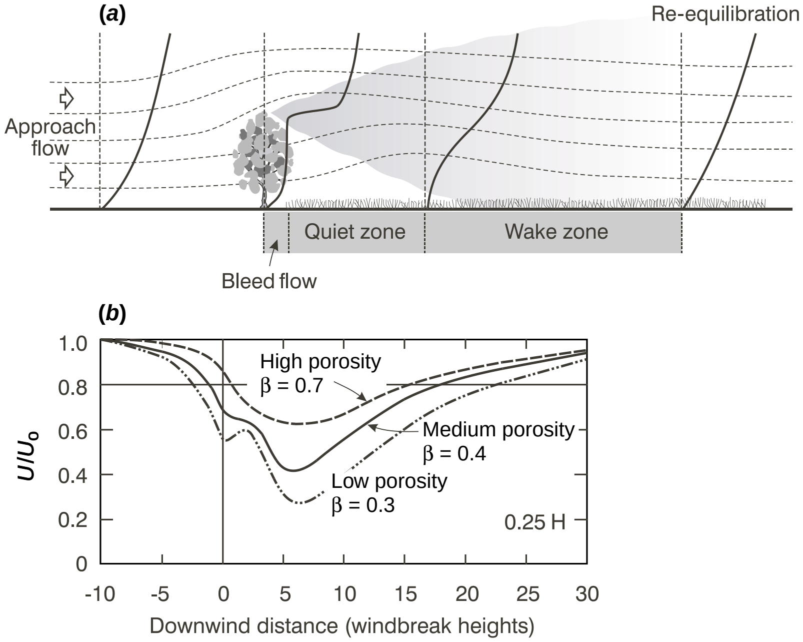

**Figure 3.** Airflow zones around a porous windbreak (from Cleugh and Hughes 2002) and relative wind shelter for three porosities. 0.25 H refers to the measurement height.

and Hughes 2002), it is significant in terms of reducing wind erosion.

*Wind climatologies*

The consistency of shelter was low at the cereal and pasture sites located in southern Australia (e.g. Rutherglen, Hamilton, Roseworthy and Esperance), which means that the downwind paddocks at these sites were often not protected (Fig. 4). Consideration of Australia's synoptic regime illustrates the reason for this, at least qualitatively. The winter and spring months in southern Australia are characterised by the alternating passage of stable anticyclones ('highs') and cold fronts associated with mid-latitude depressions ('lows') situated in the southern ocean. The typical wind pattern that results is light easterly flow, under the influence of the high, for several days followed by freshening north-westerly winds ahead of a cold front. After the passage of the front, the flow may turn westerly for a short period, maybe 1–2 days, before returning to easterly flow as the high re-establishes. The flow across a north–south oriented windbreak will therefore often be directed at an oblique angle to the windbreak and the wind direction may only be within ± 45° of normal to the windbreak for 20–30% of the time. This pattern is seen at the Roseworthy, Hamilton and Esperance sites, especially in 1995–97, and can be contrasted to the very consistent levels of shelter recorded at the Atherton site (Fig. 4), which is located in the path of the persistent south-easterly trade winds.

This raises the question of designing an effective windbreak system in places like Australia where the wind direction varies from day to day, and from season to season. Some windbreak design options are described in the conclusions, and discussed in greater detail in the 2 publications on guidelines for windbreak design that have emerged from the National Windbreaks Program (Abel *et al.* 1997; Cleugh 2002*c*).

*Effects of oblique winds on wind shelter*

The wind tunnel and field results show that for very long windbreaks, oblique flows within 45° of normal to the windbreak do not compromise the level of shelter. However, the downwind distance over which shelter is observed contracts, approximately linearly with (sin $\alpha$) where $\alpha$ is the incidence angle ($\alpha = 90°$ and 0° indicates wind directions oriented normal and parallel, respectively, to the windbreak). For tree windbreaks especially, the aerodynamic porosity of the windbreak may be reduced as a result of the longer pathlength through the vegetation plus enhanced levels of shelter are often observed in the 1–3 H zone. Finally, flow around the ends of short windbreaks (length <<20 H) may erode the lateral extent of the sheltered zone (Cleugh and Hughes 2001).

*Effects of shelter on microclimates and evaporation fluxes*

A primary objective of the NWP was to explore what effect the altered airflow has on the microclimate and evaporation fluxes, using a combination of wind tunnel and field experiments. The wind tunnel measurements showed that the sheltered quiet zone was also a region of elevated surface and air temperatures (Fig. 5). Indeed, the spatial pattern of wind-speed reduction mirrors that for the enhanced temperature such that the location of maximum

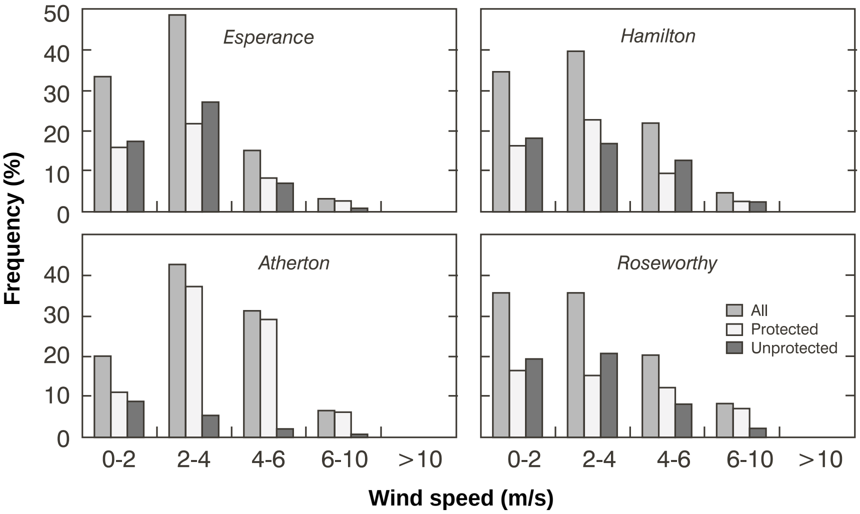

**Figure 4.** Percentage of wind speeds in each wind-speed class ('All') for the 1997 growing season (Esperance, Hamilton and Atherton sites) and 1996 growing season (Roseworthy site). The wind shelter provided by the windbreaks for each wind-speed class is indicated by the 'Protected' columns, i.e. the percentage of winds in each wind-speed class that were sheltered by the windbreak. The 'Unprotected' data shows the percentage of winds in each wind-speed class that were not affected by the windbreak.

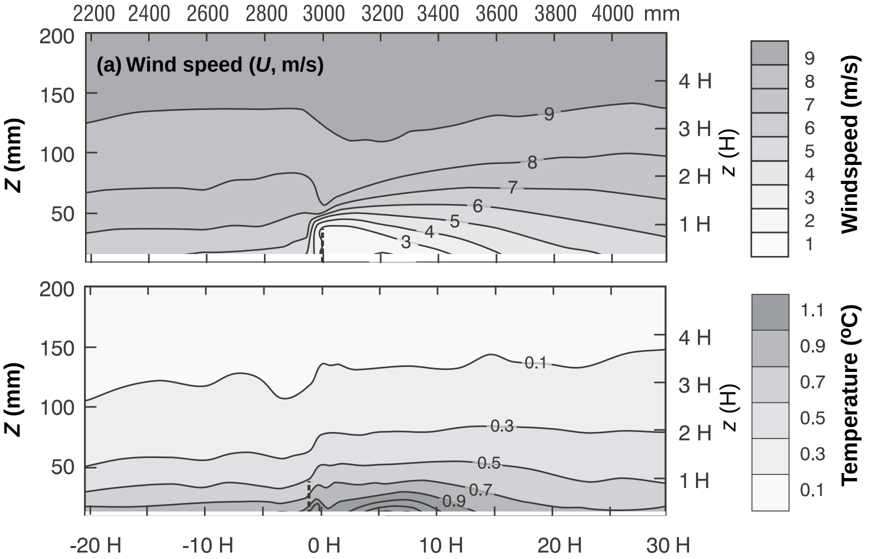

**Figure 5.** Spatial pattern of (*a*) wind speed and (*b*) near-surface air temperature measured around a medium-porosity windbreak. The vertical dashed line indicates the location of the model windbreak (from Cleugh and Hughes 2002).

temperature coincides with the location where the wind speed is most reduced. Figure 6 illustrates the relationship between changes in near-surface air temperature and wind speed in the quiet zone for all windbreak porosities used in the wind tunnel experiments. It is important to note the scale; near-surface temperature gains are much smaller in magnitude than the reductions in wind speed.

These results suggest that the concentration of an entity with a ground-based source, such as water vapour or heat, will be enhanced in the quiet zone — so air temperature and/or atmospheric humidity would be expected to increase. The results from the artificial shelter (Sudmeyer *et al*. 2002*b*) and field experiments (Cleugh 2002*a*); and field site measurements confirm the wind tunnel results and this expectation. Bird *et al*. (2001*b*) observed slight increases in the average daytime maximum air temperature in their artificial shelter sites, while Sudmeyer *et al*. (2002*b*) found that shelter tended to increase the daytime atmospheric humidity at the Esperance artificial shelter site. Measurements over the growing season at the Esperance and Roseworthy field windbreak sites, where shelter was much less consistent, also revealed slight increases in daytime temperatures (Sudmeyer and Scott 2002*a*; Nuberg *et al*. 2002).

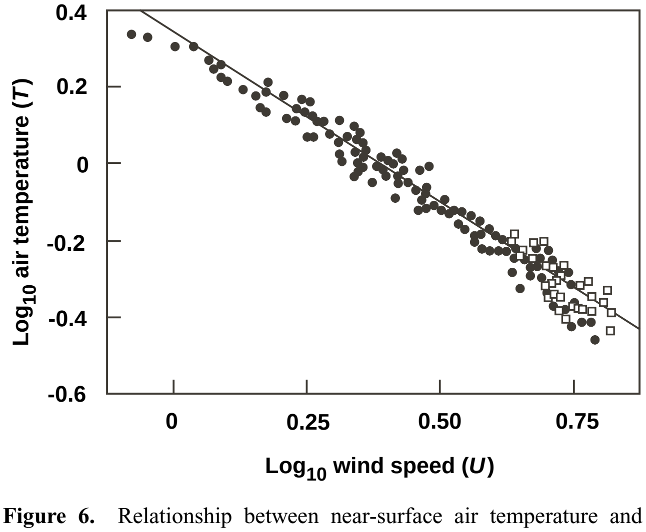

**Figure 6.** Relationship between near-surface air temperature and wind speed (measurements from wind tunnel experiments) (from Cleugh and Hughes 2002).

The field and wind tunnel experiments demonstrated important differences between the spatial patterns of wind shelter and temperature and humidity. While near-surface wind shelter was observed over distances extending as far as 25 and 30 H, the zone of enhanced temperature and humidity only extended to about 10–12 H downwind, which is just downwind of the limit of the quiet zone and at the beginning of the wake zone. The wind tunnel and field data showed air temperatures were slightly lower in the wake zone, compared to their values upwind (Cleugh and Hughes 2002). This means that near surface wind protection extends over a much greater distance downwind than microclimate changes. The corollary is that a windbreak spacing of about 10 H is required to maximise temperature and humidity increases whereas windbreak spacings of 20–25 H can achieve useful wind speed reductions.

The wind tunnel and field experimental results indicate that the turbulent fluxes of heat and water are greatly reduced in the quiet zone, but increase above their upwind values at the beginning of the wake zone. Thus, the spatial pattern of the evaporation flux also differs to that for wind shelter.

As expected from the modelling results (below), there was little evidence of increased soil water storage as a result of reduced evaporation fluxes (= canopy transpiration plus soil and canopy evaporation) in the sheltered quiet zone of the field windbreaks (Hall *et al*. 2002; Nuberg *et al*. 2002) except at a number of Esperance sites in 1994 that did show a small increase in stored soil water between 3 H and 15 H (Sudmeyer and Scott 2002*b*). In part, this is because the effect of wind shelter on transpiration depends on whether the unsheltered canopy transpiration rate is greater or less than the equilibrium rate which, in turn, depends on the available soil water, canopy conductance and humidity of the air upwind of the windbreak. The combination of inconsistent wind shelter, and the variable nature of the impact of that shelter on plant transpiration, means that both transpiration and soil water storage in the quiet zone will be relatively insensitive to these 'aerodynamic' effects of shelter. The waterlogging observed in some of the artificial shelter sites does indicate that evaporation can be reduced with consistent levels of wind shelter (Sudmeyer *et al*. 2002*b*) but this is likely to be reduced soil evaporation rather than canopy transpiration (unless the canopy is wet through irrigation or rainfall). Confounding the interpretation of shelter effects on water use is the observation that leaf area can be increased by shelter, which can lead to enhanced water use in the sheltered quiet zone.

The key modelling results, in terms of microclimate and evaporation fluxes (Cleugh 2002*b*), were the following:

(i) While soil evaporation is quite sensitive to wind shelter, this is not necessarily so for plant transpiration.
(ii) Measuring changes in water use in the field will be difficult as a result of soil and wind-climate variability, and the confounding effects of wind shelter on biomass, all of which can overwhelm any subtle effects of shelter on evaporation fluxes.
(iii) A direct physiological response to wind shelter, through improved water use efficiency and reduced evaporative demand, may be an important mechanism in climates where hot, dry winds are frequent at the time of grain filling.

### *Effects of shelter on plant growth and yield*

The artificial shelter experiments showed that constant shelter led to increased biomass but not necessarily to increased grain yield or reduced soil evaporation early in the season. Maize plants growing close to the windbreaks at the Atherton site also grew taller than plants further downwind, and were more prone to lodging during the passage of tropical cyclone Justin (A. J. Snell and S. J. Brooks pers. comm.). This finding points to the importance of selecting cultivars that have been bred for stronger stems and are thus more resistant to lodging. The measurements from the artificial shelters at Hamilton (Bird *et al*. 2002*b*) showed slightly enhanced dry matter production in the cold winter period when temperatures are likely to limit pasture growth. The potential for shelter to increase pasture growth rates at these times, when stockfeed might otherwise be limited, may be critical to the carrying capacity of a farm; however, such increases require continuous shelter and will only be confined to the quiet zone.

The results from the field sites (Table 2) were more equivocal in terms of shelter impacts on biomass and harvest yields. Of course, these observations span only a 5-year period. Such trends may require a much longer record (>20 years) to become apparent. This was the reason for the long-term crop growth simulations conducted by Carberry *et al*. (2002), whose results are described below.

Overall, the field results identify 2 broad areas of crop and pasture response: a zone of reduced yield associated with competition with the windbreak trees that extended from 1 H to 3 H, and a zone of unchanged or slightly increased yield stretching downwind to 10 H or 20 H. The summary in Table 2 does not take into account those losses in the competition zone (±3 H). The individual research papers should be consulted for this information and other specific details for each field measurement site. Some of the factors that lead to the results reported in Table 2 are outlined below.

*Wind climate variability.* As already discussed, the inconsistency of shelter over the growing season limited the period of wind protection for many of the field sites, which is in sharp contrast to the artificial shelters and the Atherton site. This has implications for the use of tree windbreaks in a climate such as experienced in southern Australia where consistent winds from 1 direction are not typical of the synoptic regime. Protection from several wind directions requires establishing 1 or more windbreaks(s) around the perimeter of the paddock. Sometimes this is not a viable solution because of establishment and maintenance costs and/or losses due to competition. In such environments, where winds are highly variable, yield gains will often be the result of protection from infrequent, but damaging, wind. Predicting these benefits, especially the economic benefits, requires accurate analyses of the frequency of such events (e.g. Jones and Sudmeyer 2002). Even then, because it is the timing of such events that will dictate the magnitude of the damage, any predictions can only be on a probability basis.

*Soil variability.* The experience at the Roseworthy field site (Nuberg *et al*. 2002) illustrates the importance of quantifying the spatial variability in soil properties and depth, or the value of making measurements at a number of sites (Sudmeyer *et al*. 2002*a*). Such variability can either result in spatial trends in crop yields being incorrectly ascribed to a shelter effect, or it can mask a shelter effect. As argued in Nuberg *et al*. (2002), the soil variability found at Roseworthy may be typical of much of the cereal growing areas of South Australia.

*Crop type*. It is not surprising that different crops responded differently to shelter. While there were no shelter-related yield gains in pasture or the cereal (maize, wheat and barley) crops at the field windbreak sites, yield gains were reported for the lupin and canola crops grown at the Esperance field windbreak site and the mungbeans at the artificial shelter site at Hermitage. The magnitude of these yield changes was fairly small, in the zone from 10 H to 20 H only, and only resulted in a net increase in yield at the Esperance site (Sudmeyer and Scott 2002*b*) in a very dry year (1994). The results from the Atherton site illustrate the potential for shelter to significantly improve returns from potatoes.

*Increased rates of phenological development*. Evidence for an increase in development rates associated with elevated temperature in the quiet zone is equivocal. The measurements at the Roseworthy site showed that elevated temperatures in the quiet zone were correlated with a reduction in the time to anthesis, while at the Esperance site development rates were influenced by shading and tree water use within 3 H but were unchanged beyond 3 H. Development rates were not changed in the artificial shelters.

*Effect of altered evaporation rates*. Reduced soil evaporation in the sheltered quiet zone (away from the interface region where trees and crops compete for light, water and nutrients) may improve crop establishment and early growth. There was no evidence of increased biomass in the artificial shelters leading to increased water use or earlier soil water depletion. Thus, in the artificial shelters at least, crop water use efficiency was improved. However, at most field sites any changes in soil moisture in shelter were too small to be measured.

The extensive survey of windbreak sites in Western Australia (Sudmeyer *et al*. 2002*a*) showed grain yield in sheltered crops increased with decreasing rainfall and found very little yield response to shelter in years with above-average rainfall. This result implies that shelter was providing some water use benefit to crops at these sites in dry years, however the greatest increases in grain yield were seen at sites where the windbreaks protected crops from wind erosion and sand blasting damage. Wind erosion is associated with dry conditions and consequently reduced vegetative cover.

*Reduction in direct wind damage*. Wind shelter can reduce production losses due to plant damage, in the case of high value horticultural crops, and sandblasting, in the case of wind erosion prone soils. Measurements of potato leaf damage at the Atherton site showed that the spatial pattern of increasing damage with distance from the windbreak was correlated with reduced potato quality and yields (A. J. Snell

**Table 2. Summary of results[A] from field windbreak and artificial shelter sites**

| Field windbreaks | | | | Artificial shelters | | |
|---|---|---|---|---|---|---|
| 1994 | 1995 | 1996 | 1997 | 1995 | 1996 | 1997 |
| *Esperance site* | | | | | | |
| Lupins (yield gain) | Canola (slight yield gain) | Barley (no yield response) | Lupins (yield gain) | Lupins (more biomass, no yield response) | Wheat (more biomass, no yield response) | Wheat (waterlogging worsened, reduced yield and biomass) |
| *Roseworthy site* | | | | | | |
| Confounded by soil variability (see individual papers for discussion) | | | | — | Wheat (more biomass but less yield) | |
| *Rutherglen site* | | | | | | |
| Confounded by soil variability so field windbreak site abandoned | | | | — | Wheat (more biomass; no yield response) | |
| *Hamilton site* | | | | | | |
| Grazed perennial pasture (no response in dry matter production) | | | | — | Perennial pasture (slight increase in dry matter production) | |
| *Hermitage site* | | | | | | |
| | | | | — | | Irrigated wheat (no yield response)<br>Mungbeans (yield gain) |
| *Atherton site* | | | | | | |
| Maize (no yield response)<br>Potatoes (yield response) | | | | — | | |

[A] Site details were compiled from the following papers: Bird *et al*. (2002*a*, 2002*b*); Nuberg *et al*. (2002); Snell and Brooks (unpublished data); Sudmeyer and Scott (2002*a*, 2002*b*); which all appear in this volume and to which readers are referred for a complete analysis of these results.

and S. J. Brooks pers. comm.). The sandy soils in Esperance region are particularly vulnerable to wind erosion and the field results (Sudmeyer and Scott 2002*a*, 2002*b*) demonstrated that the shelter provided by a tree windbreak, and the associated reduction in wind erosion and sandblasting, can make the difference between 'crop' and 'no crop' in bad years. In such years, the productivity gains resulting from shelter are obviously very large.

*Competition between trees for light, water and nutrients*. Crop and pasture growth was reduced near the windbreaks at all of the field sites in all years. The magnitude and extent of these losses varied from site to site and year to year. The extent appeared to be greater for older trees and the extent and magnitude increased with decreasing rainfall (Sudmeyer *et al*. 2002*c*). Shading delayed anthesis at the Esperance site but reduced soil water near the trees was of more importance in reducing yield. Severing tree roots (root pruning) where the roots were confined close to the soil surface virtually eliminated competition losses (Sudmeyer *et al*. 2002*c*).

*Overall impact on paddock yields*. Combining all these results leads to the overwhelming conclusion that overall paddock yield changes were small, but the following points are important:

(i) Enhanced yields are more likely in dry years, especially as these years are associated with a greater risk of severe wind damage events.

(ii) Cereals and pasture were the least responsive to the microclimate changes bought about by wind shelter. Lupins, canola, mungbeans and, possibly, faba beans showed larger yield responses, although in the case of lupins, this may have been a response to reduced wind damage. A high value horticultural crop such as potatoes was found to be very sensitive to damage, hence the protection offered by shelter conferred a large economic advantage even when potatoes are grown in rotation with cereals.

(iii) Protection from a damaging wind event can mean a crop where no crop might otherwise be possible. Jones and Sudmeyer (2002) present an economic analysis showing the frequency of sandblasting events required for windbreaks to be economic. For the Esperance region, they found that 3–5 severe sandblasting events over a 35-year period were sufficient to render windbreaks profitable.

(iv) Jones and Sudmeyers' economic analysis also illustrates the importance of managing the competition zone, from the use of root pruning in their case study to the overall economic viability of windbreaks. Reducing competition for water and nutrients can shift the impact of windbreaks on total paddock yield, taking into account productivity losses associated with the area taken by the windbreak trees and the costs of establishing the windbreak, from neutral or even negative to a productivity and economic gain.

(v) The economic gains that result from sheltering high value horticultural crops, such as potatoes and peanuts, are clear from the Atherton results. These were sufficient to make windbreaks economic when grown in rotation with a cereal crop.

*Are windbreaks profitable? Results from APSIM simulations*

The APSIM model was adapted to predict the effects of wind shelter on crop yields. Validation of this modelling approach was limited to the measured results from the artificial shelter sites as none of the field studies found an unequivocal yield response to shelter (Meinke *et al*. 2002; Carberry *et al*. 2001). Hence, there is some uncertainty in the model's validity. The effect of wind, and thus shelter, was modelled using a version of the Penman equation to estimate the atmospheric demand. These daily time-step simulations compared favourably with the more physically rigorous, 15 min time-step simulations using SCAM (Cleugh 2002*b*), which provides some confidence in the approach. Nonetheless, a limitation to the APSIM model lies in the use of a daily time-step. The results presented in Cleugh (2002*a*) clearly show little diurnal variation (0600–1800 hours) in wind shelter, but much larger diurnal variability in the effect of this wind shelter on temperature and, especially, the atmospheric demand.

Despite these concerns, the APSIM approach provides a useful predictive capability, which enabled an investigation of the sensitivity of various cropping systems to shelter (Carberry *et al*. 2002). Importantly, these simulations include the effect of seasonal and annual climate variability on the response of crop yields to shelter because they were forced to use the historical climate record for each site. The simulated yield responses to shelter were often small, and became negligible when variability of wind direction was included in the analysis for those few sites where historical wind direction data were available. The exceptions were locations characterised by consistent wind direction, high atmospheric demand and low soil water storage in the latter part of the growing season, such as Dalby in Queensland and Minnipa in South Australia.

These conclusions echo the results from the field and artificial windbreak sites. In particular, the simulations and simple economic analyses demonstrate that yield gains resulting from microclimate changes alone were not sufficient to offset the costs and loss of land associated with establishing a windbreak and loss in productivity in the zone of significant tree–crop competition (±3 H). Given that these results were for a windbreak along 1 boundary of a paddock only, it is clear that improvements to yield that might be gained by adding more windbreaks around the paddock's perimeter will be offset by the extra costs associated with establishment and competition.

The APSIM simulations also demonstrated that minimising the area taken up by the windbreak itself, and managing the competition zone through, for example, root pruning, can reduce the costs associated with windbreaks. Finally, windbreaks may become a more economically viable proposition if financial gains can be realised from one of the other multiple benefits of tree windbreaks, or if damaging events are frequent as illustrated by Sudmeyer *et al*. (2002*a*). If windbreaks are planted to achieve multiple benefits, for example by providing marketable timber or a fodder source, these small productivity gains can offset the establishment costs.

## Conclusion

### *Windbreak effects on crop productivity*

Figure 7 illustrates the main mechanisms, in terms of windbreak effects on microclimate, crop growth and final yields, for the 3 main airflow zones presented earlier. In terms of the hypothesis established at the outset, it is clear that microclimate changes due to shelter have a smaller impact upon productivity than expected. This arises partly from the variable wind climate, which means that paddocks with a single windbreak along 1 border are only sheltered intermittently. If these intermittent and subtle changes are combined with a spatially variable soil type, then the impact on final yields will be small. While adding windbreaks around the paddock boundary may provide a larger and more consistently sheltered zone, the productivity gains may not be sufficient to outweigh the added costs of establishment and competition.

Furthermore, the wind tunnel and field experiments show that temperature and humidity fields are affected over a smaller distance downwind (<10 H) than wind shelter (>20 H). Given that competition for light, water and nutrients in the ± 3 H zone may limit crop growth and productivity, the area of paddock over which microclimate effects can have an impact is small. The resulting changes in soil and plant evaporation are also likely to be confined to the quiet zone — indeed there is potential for enhanced evaporation fluxes in the wake zone. Reduced soil evaporation may conserve soil water in the early season, while a reduction in evaporative demand later in the season may improve the water use efficiency of plants growing in the quiet zone. But these will be intermittent mechanisms whose importance depends on the stage of plant development and the wind direction, frequency and timing of dry advective events. The absence of a strong signal, in terms of a yield response to shelter, simply reflects the combination of these sources of variability.

Shelter will only benefit productivity if it affects a factor that currently limits growth and productivity. Thus, in the pasture growing regions of Victoria or the NSW Tablelands, consistent shelter in the winter months could enhance pasture growth. Similarly, yield gains could result from reduced evaporative demand in an environment where the probability of dry advective events at anthesis and grain filling is high. Such sites, as identified by the simulations presented in Carberry *et al*. (2002), include locations on the Darling Downs in Queensland and in the cereal growing regions of South Australia. Water availability is probably one of the most important limits to growth in Australian agriculture — unfortunately shelter from wind does not

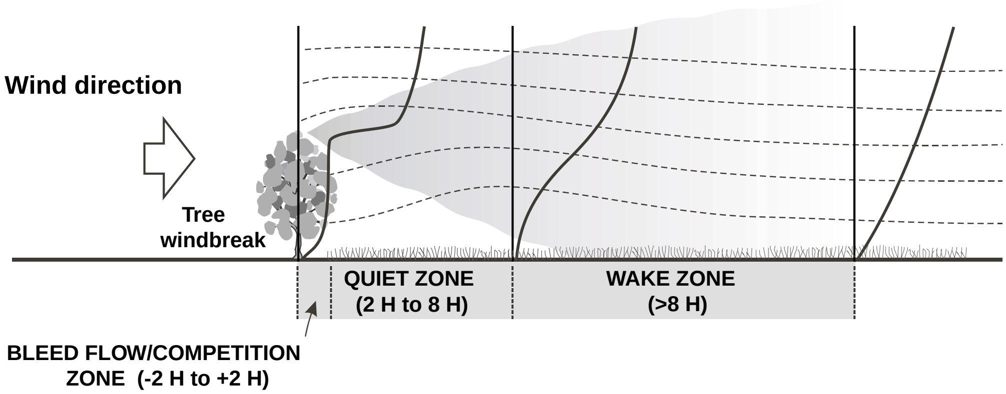

**Figure 7.** Schematic showing the principal mechanisms affecting microclimate, crop growth and yield in the airflow zones around a porous windbreak. **Bleed flow/competition zone (–2 H to +2 H):** competition for water, light and nutrients reduces yields at all field sites; windbreak structure is important in this zone as gaps can lead to wind erosion and sandblasting damage. **Quiet zone (2 H–8 H):** calmer, warmer and/or more humid; reduced soil evaporation may improve crop establishment; atmospheric demand can be increased or decreased, depending on the humidity of the regional flow. In dry conditions, a reduction in atmospheric demand may lead to improved water use efficiency — either more biomass and/or yield for the same water use as the crop upwind, or less water use than the upwind crop for the same biomass and/or yield; enhanced phenological development and biomass production are possible, but this does not always translate into yield gains. **Wake zone (>8 H):** effects of wind shelter on temperature and humidity are small; shelter from wind reduces risk of direct damage to plants from leaf tearing, stripping and plant lodging and sandblasting.

always mean reduced evaporation fluxes, and so windbreaks cannot be relied on to improve yields by reducing this limiting factor.

A clearer yield response resulted when either constant wind shelter could be maintained over the season, or when the damaging effects of wind were an important factor limiting productivity. The 2 main forms of wind damage seen during the NWP were damage due to sandblasting, and leaf tearing and stripping. The potential for windbreaks to improve productivity by reducing direct wind damage is a key result from this research. It means that a direct wind effect on productivity is potentially more important than effects due to temperature and humidity, for (at least) 2 reasons. First, wind shelter occurs over a larger area of the paddock, so windbreaks can be spaced further apart to capture this benefit. Second, adequate levels of wind protection were found even for a porous windbreak. More research is required to identify the important sources of direct wind damage, and to quantify the probability of occurrence of these forms of damage, in the agricultural regions of Australia.

### *Implications for windbreak design*

The results from the NWP have implications for designing windbreaks for Australian agricultural systems. The critical aspect is to identify which factors affect agricultural productivity and, importantly, which wind conditions — especially wind direction — are associated with these limiting factors. This determines what shelter mechanism is required, e.g. microclimate modification (warmer air and soil temperatures for earlier germination, enhanced phenological development and/or increased biomass for feed); or protection from damage to young seedlings and maturing plants through sandblasting, leaf tearing or lodging; or to protect stock from chilling winds. Having identified these limiting factors and from which wind conditions shelter is needed, the number of windbreaks, their layout and optimum porosity can be determined. The key issues are:

*(i) Layout and spacing.* If protection is required from just a narrow range of wind directions (ranging, say, over 90°) then a single, long windbreak will be adequate. As long as the windbreak is at least 20 H in length, then it will provide windspeed reductions in a zone extending from about 5 H upwind to 30 H downwind. Much smaller changes in temperature and humidity will occur in a zone extending from about 3 H upwind to 10 H downwind.

If protection is required from winds that blow from a much larger range of directions, then more than just a single windbreak is required. One option is to place single, long windbreaks around 2 or more edges of the paddock, which increases the sheltered area without hindering activities within the paddock such as ploughing, sowing and harvesting. This does, however, increase the crop–tree interface length and thus the area of land affected by competition for light, water and nutrients. The production losses that arise as a result of this competition need to be compared to any production gains that flow from the windbreaks.

A third alternative, more suitable for pasture-grazing systems, is to space windbreaks fairly closely together (e.g. at 6 H or 12 H spacings), or plant scattered trees. Both approaches can provide very sheltered zones, for example spacing windbreaks at 6 H or even 12 H would lead to permanent quiet zones between the windbreaks. These spacings clearly maximise the shelter and the microclimate modification. Of course, the competition zone is also maximised with this layout, and so the associated costs must be included in the analysis of whether this layout is viable (see Abel *et al*. 1987 for diagrams and further details).

*(ii) Length, width and height.* As indicated above, windbreaks need to have considerable length so that the sheltered zone is not eroded by flow around the windbreak ends. Results presented by Cleugh and Hughes (2002) suggest that 20 H is a minimum windbreak length. Single row windbreaks will often not provide an adequately uniform porosity, and so a multi-row windbreak is recommended. Finally, the taller the windbreak, the larger will be the size of the sheltered zone. As discussed earlier, rapidly growing windbreaks, or placing windbreaks on a mound, may be an important design feature.

*(iii) Porosity.* There are 3 critical aspects with reference to porosity. First, a uniform porosity is critical, i.e. gaps must be avoided. Second, porosities in the range of 30–70% lead to wind speed reductions in direct proportion to the density (i.e. a porosity of 70% will lead to, roughly, a 30% reduction in wind speed). The size of the sheltered quiet zone does not change significantly for this range in porosity, and so the optimum porosity depends entirely on how much wind speed reduction is needed. Note that the more porous windbreaks are not likely to lead to any detectable changes to the temperature and humidity. Last, for specific applications such as controlling snow and dust deposition, a particular vertical gradient in porosity may be needed.

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### Appendix 1. Sampling framework for assessing plant damage

1. At each of the measurement stations (except after an obvious damage event, when more widespread sampling along the transect and possibly across the paddock may be required), each group should:
    - (i) Score any leaf or plant damage on a scale of 0–5, where 0 is the least damage and 5 is the worst damage. These 2 extremes should be set on that day — this sliding scale means that resolution is maximised, but the cost of this is that there is no absolute calibration. Groups are requested to make either sketches or (preferably) photos of the damage that constitutes a score of '5' and '0'. This will assist in normalising the data later.
    - (ii) Document the type of damage, e.g. 'flag leaf completely torn off'; 'leaves torn'; 'leaves split along spine'; 'obvious scarring from the sandblasting'; 'burns from rubbing and abrasion'; 'plant lodged at the base of the stem' etc.
    - (iii) Document the number of plants or leaves damaged as described in (i) and (ii) at each measurement station.

2. If a sandblasting event occurs:
    - (i) Note visibility during the event (the dust loading can be estimated from this) and take a sand sample (if possible);
    - (ii) Ensure that the automatic weather station is/was logging and the data is archived;
    - (iii) Check plants for obvious signs of damage and quantify as noted in (1).

3. If a lodging event occurs:
    - (i) Note if the lodging was caused by wind plus rain, or wind or rain alone;
    - (ii) Note whether the lodging is at the stem or root. If the latter, and the event was very recent, take soil moisture readings if at all possible;
    - (iii) Quantify lodging using the indices given in the Miller *et al*. (1995).