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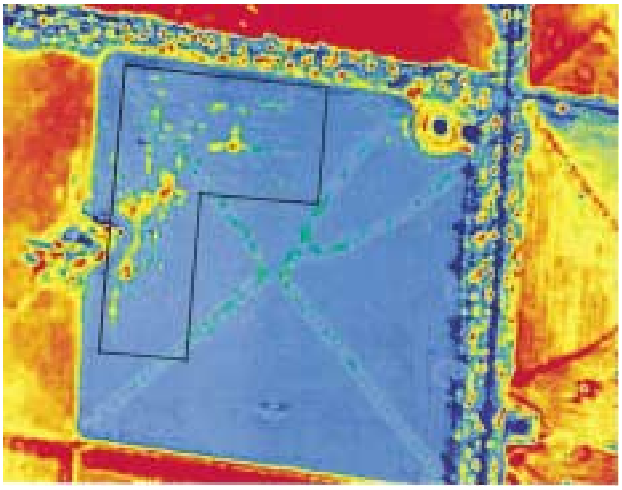

Volume 42, 2002

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Australian Journal of Experimental Agriculture, 2002, **42**, 841–858

Effect of artificial wind shelters on the growth and yield of rainfed crops

R. A. Sudmeyer[A,D], *M. C. Crawford*[B], *H. Meinke*[C], *P. L. Poulton*[C] *and M. J. Robertson*[C]

[A]Agriculture WA, PMB 50, Esperance, WA 6450, Australia.
[B]DNRE, Agriculture Victoria, RMB 1145, Rutherglen, Vic. 3685, Australia.
[C]APSRU/CSIRO Sustainable Ecosystems and DPI, PO Box 102, Toowoomba, Qld 4350, Australia.
[D]Author for correspondence; e-mail: rsudmeyer@agric.wa.gov.au

Abstract. There is great interest in quantifying and understanding how shelter modifies crop growth and development under Australian conditions. Small constructed enclosures (shelters) can consistently reduce wind speed, allowing experiments to be run with replicated sheltered and unsheltered treatments in close proximity. The aim of this study was to quantify the effect on microclimate of consistently reducing wind speed by 70% and explain the consequences for dryland wheat (*Triticum aestivum*), lupin (*Lupinus angustifolius*) and mungbean (*Vigna radiata*) growth and development, at sites in Queensland, Victoria and Western Australia. Crops were grown inside and outside of artificial shelters, 10 by 10 m and extending 1 m above the crop canopy throughout the growing season.

Mean daily air and soil temperatures and atmospheric vapour pressure inside the shelters were largely similar to unsheltered conditions. However, clear diurnal trends were evident; daily maximum temperature and vapour pressure deficit (VPD) were increased in shelter when crops were establishing or senescing. When leaf area index (LAI) was reduced in the shelters, soil temperature was greater than in the open, however when LAI was increased in the shelters, soil temperature was less than in the open.

Grain yield in shelters ranged between 78 and 120% of unsheltered yield, depending on seasonal conditions and crop species; the mean yield for all sites, crops and years was 99% of unsheltered yield. In the absence of waterlogging, sheltered crops tended to develop more leaf area than unsheltered crops, with an increase in the ratio of leaf area to above-ground biomass. This greater leaf area did not increase soil water use. While LAI was increased by shelter, only 2 of the 6 sheltered crops that were not waterlogged yielded significantly more grain than the unsheltered crops. This may be because the sheltered crops experienced greater maximum temperatures and VPD during anthesis and grain filling than unsheltered crops. Also, net photosynthesis may not have increased in the shelters after canopy closure (LAI>3–4). Lupins, which developed more leaf area inside shelters, may have experienced strong competition for assimilates between developing branches, flowers and fruit. When rainfall was above average and the soil became waterlogged for part of the growing season, grain yield was reduced inside the shelters. Reduced evaporation inside the shelters may have extended the duration and severity of waterlogging and increased stresses on sheltered plants when potential yield was being set.

The reductions in wind speed achieved inside the artificial shelters were greater than those likely in conventional tree windbreak systems. Analysis of crop growth illustrated that microclimate modification at this high level of shelter can be both beneficial and harmful, depending on the crop species and climatic conditions during the growing season.

Additional keywords: lupins, mungbeans, wheat, windbreak.

Introduction

Microclimate changes in either natural or artificial windbreak systems can influence plant growth and development. There is great interest in quantifying and understanding these physiological responses under Australian conditions so that windbreak systems can be developed and promoted from a sound knowledge of their impact on the farm economy and environment (Nuberg 1998). Measuring the effect of wind shelter on crops can be difficult. Changes can be masked by paddock-scale variations in soil fertility and soil water content, animal and disease damage, competition between windbreak trees and crop and varying levels of shelter as wind direction and wind-speed change during the growing season (Kort 1988). In particular it is difficult to find windbreak systems providing shelter throughout the year with nearby areas of unsheltered crop growing on the same soil type with the same agronomic history.

Small constructed enclosures can consistently provide the maximum wind-speed reductions that can be achieved in tree

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windbreak systems, allowing experiments to be run with replicated sheltered and unsheltered treatments in close proximity (Argete and Wilson 1989). By providing greater wind-speed reductions than are commonly achieved with field windbreaks, it should be possible to quantify maximum microclimate and crop responses to shelter. These data benchmark the greatest achievable windbreak effects. The results of this experiment, which was part of the broader National Windbreaks Program (Cleugh *et al.* 2002), enable a better understanding of the much more subtle changes commonly experienced in the lee of field windbreaks. Additionally, it provides data sets to validate the crop simulation models developed under the NWP for environmental and economic assessments of windbreaks (Carberry *et al.* 2002; Meinke *et al.* 2002).

To allow such benchmarking, 3 similar experiments were conducted at sites in Western Australia, Victoria and Queensland to quantify the effect of maximum wind-speed reductions on microclimate and crop growth and development.

Methods

Sites

Experiments were conducted at Esperance, Western Australia, in 1995 (lupin; *Lupinus angustifolius*), 1996 (wheat; *Triticum aestivum*) and 1997 (wheat), Dookie, Victoria, in 1996 (wheat), Rutherglen, Victoria, in 1997 (wheat) and Warwick, Queensland, in 1997 (wheat and mungbean; *Vigna radiata*) and 1998 (mungbean) (Table 1).

Esperance. The West Australian site was located at Esperance Downs Research Station, 30 km north–north-west of the town of Esperance, on the south coast of Western Australia (33°37′S, 121°48′E). The soil is 0.5–0.6 m of fine sand containing more than 50% feruginous nodules overlying a sandy clay subsoil containing few feruginous nodules (mesonatric, yellow Sodosol: Overhue *et al.* 1993; Isbell 1996).

The climate is Mediterranean with warm, dry summers and cool, wet winters. Average annual rainfall is 491 mm, with 367 mm falling during the growing season (May–November). Growing season rainfall was 376 mm in 1995, 336 mm in 1996 and 419 mm in 1997. Rainfall in 1995 was above average early in the season and below average at the end of the growing season (September–November rainfall, 100 mm) (Fig. 1*a*). In contrast, rainfall in 1996 was below average from sowing until anthesis but above average during grain filling (September–November rainfall, 152 mm). Rainfall was also below average early in the 1997 growing season, but heavy rainfall when plants were tillering caused severe waterlogging, which lasted until after anthesis.

Dookie. The Dookie site was located at the Dookie College Campus of the University of Melbourne, in north-eastern Victoria (36°23′S, 145°42′E). The climate is Mediterranean with warm, dry summers and cool, wet winters. The soil is light sandy clay loam overlying a medium clay subsoil (mottled, duric, brown Chromosol: Isbell 1996).

Average annual rainfall is 557 mm, with 371 mm falling during the growing season (May–November). Total growing season rainfall was 434 mm in 1996, but was below average during October and November (Fig. 1*b*).

Rutherglen. The Rutherglen site was located at Browns Plains, 10 km north-east of the Rutherglen Research Institute in north-eastern Victoria (36°05′S, 146°34′E). The soil is heavy silt loam overlying a medium to heavy clay (haplic, brown Dermosol: Isbell 1996).

The climate is Mediterranean with warm, dry summers and cool, wet winters. Average annual rainfall is 598 mm, with 397 mm falling during the growing season (May–November). Total growing season rainfall was 233 mm in 1997, the October–November period also had below average rain (Fig. 1*b*).

Warwick. The Queensland site was located near Warwick, on the Hermitage Research Station on the Darling Downs, south-eastern Queensland (28°18′S, 152°06′E). The soil is alluvial, cracking clay (talgai-shallow phase brown Vertisol: Isbell 1996).

The climate is subtropical with dominant summer rain, hot summers and cool winters. Average annual rainfall is 728 mm, with rainfall during the winter cropping season (June–November) averaging 345 and 296 mm during the summer cropping period (January–May). Rainfall during the 1997 winter cropping season was 371 mm, and below average from sowing until just before anthesis, after which rainfall was above average. Rainfall during the summer cropping season was 203 mm in 1997 and 199 mm in 1998 (Fig. 1*c*).

Experimental design

At each site, 4 sheltered and 4 unsheltered treatments were established. Shelters were erected immediately after sowing at the Esperance and Dookie sites and after emergence at the Rutherglen and Warwick sites. Treatment replicates were 20–50 m apart to ensure the shelters had minimal influence on wind speed over the open treatments.

Shelter was provided by erecting square enclosures made of shade cloth (Nylex 70% shade, green). The sides of the enclosures were 10 m long and 1 m high. As the crops grew, the sides of the shelter were raised, so that the top of the shade cloth was maintained 0.8–1.0 m above the crop canopy, and the bottom of the shade cloth extended 0.2 m below the crop canopy. Since wind speed is effectively zero below the zero plane displacement layer plus the roughness length

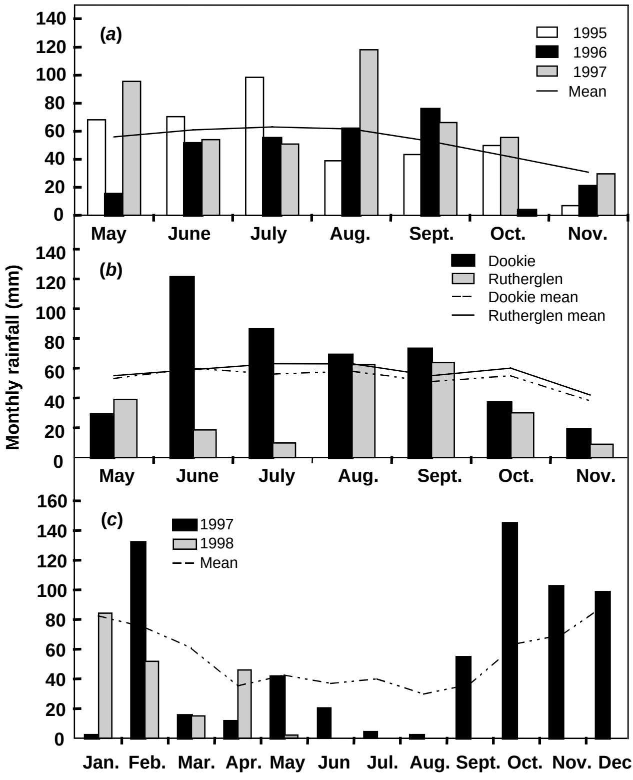

Figure 1. Monthly and long-term mean rainfall at (*a*) Esperance between 1995 and 1997, (*b*) Dookie in 1996 and Rutherglen in 1997 and (*c*) Warwick in 1997 and 1998.

[where roughness length is about 0.11 × crop height and the zero plane displacement is about 0.66 × crop height (Oke 1987)], air movement under the shelters would have been minimal during the growing season.

Inside each shelter, a 6 by 6 m sampling grid was laid out using pegs and string lines. Each square of the grid (quadrat) was 1 m^2. Dry matter samples were taken from alternate squares of the grid so that squares of undisturbed crop lay between each sample quadrat. In this way, 18 sample quadrats were available in each treatment replicate. The edges of the grid were 2 m from the sides of the shelter to minimise shading effects (Cleugh 1998). Similar grids were laid out in areas of unsheltered crop. For each phenological or growth measurement, sample quadrats were at different locations within the shelters to

Table 1. Agronomic details and date and crop stage at which measurements were made at each site

Crop	Date	Days after sowing	Crop developmental stage	Soil moisture	Biomass	Leaf area	Height	Grain yield
			Esperance 1995					
Lupinus angustifolius cv. Merrit (lupin), sown at 99 kg/ha	31 May	2		+				
	27 June	29	100% emergence	+	+	+	+	
	6 Sept.	100	100% anthesis	+	+	+	+	
	5 Oct.	129	End anthesis	+	+	+	+	
	4 Dec.	189	Mature	+	+			+
			Esperance 1996					
Triticum aestivum cv. Machete (wheat), sown at 75 kg/ha	18 June	3		+				
	10 July	25	100% emergence	+	+	+	+	
	27 Aug.	73	Mid-vegetative (stem elongation)	+	+	+	+	
	7 Oct.	114	100% anthesis	+	+	+	+	
	27 Nov.	165	Mature	+	+		+	+
			Esperance 1997					
T. aestivum cvv. Machete and, Carnamah (wheat), sown at 50 kg/ha	10 June	1		+				
	2 July	23	100% emergence	+	+	+	+	
	20 Aug.	72	Mid-vegetative (stem elongation)	+	+	+	+	
	15 Sept.	98	100% anthesis		+	+	+	
	2 Oct.	115	End anthesis start grain fill	+	+	+	+	
	19 Nov.	163	Mature	+	+		+	+
			Dookie 1996					
T. aestivum cv. Katunga (wheat), sown at 80 kg/ha	7 May	0	Sown					
	13 Aug.	98	Mid-vegetative		+			
	30 Oct.	176	Anthesis		+			
	11 Dec.	218	Mature		+			+
			Rutherglen 1997					
T. aestivum cv. Currawong (wheat), sown at 100 kg/ha	5 May	0	Sown	Every 2 weeks				
	14 July	68	Early vegetative		+			
	9 Sept.	125	Late vegetative		+	+		
	15 Oct.	161	Anthesis		+			
	17 Nov.	194	Grain fill (early dough)		+			
	5 Dec.	212	Mature		+			+
			Warwick 1997					
Vigna radiata cv. Berken (mungbean), sown at 30 plants/m^2	28 Jan.	0	Sown					
	19 Mar.	50	Anthesis		+			
	2 Apr.	64	Grain fill		+	+		
	28 Apr.	90	Mature		+			+
T. aestivum cv. Hartog (wheat), sown at 130 plants/m^2	3 July	0	Sown					
	2 Oct.	91	50% anthesis		+	+		
	16 Oct.	105	Grain fill (hard dough)		+	+	+	
	14 Nov.	134	Harvested		+			+
			Warwick 1998					
V. radiata cv. Emerald (mungbean), sown at 40 plants/m^2	6 Feb.	0	Sown					
	19 Mar.	41	Mid–late vegetative		+			
	2 Apr.	55	Grain fill		+	+		
	20 Apr.	73	Grain fill		+			
	14 May	94	Mature		+			+

account for variations in shading and wind speed within the shelters (Fig. 2).

Agronomic details for each crop are given in Table 1.

At Esperance in 1995, 1 shelter was removed at 100% plant emergence and another at 100% anthesis. This meant sheltered and unsheltered treatments were replicated 4 times when measured at sowing and 100% establishment, 3 times at 100% anthesis and twice at harvest. In 1996, sheltered and open treatments remained unchanged from sowing through to harvest. In 1997, 2 replicates of each treatment were established on wheat variety Machete and 2 on wheat variety Carnamah. In August 1997, 3 replicates of each treatment were affected by waterlogging, starting 56 days after sowing until after anthesis. At anthesis, measurement was stopped on these treatment replicates. The shelters were moved, and measurements resumed in areas of crop with no visual waterlogging damage. Measurements continued on the single unsheltered and sheltered treatment replicates that were not obviously waterlogged. Only crop variety Machete was measured after anthesis.

At Dookie and Rutherglen, sheltered and open treatments remained unchanged from sowing through to harvest.

At Warwick, irrigation was applied by sprinkler before sowing to assist establishment, after which crops were grown under rainfed conditions. The shelters were erected after the crops had established, and been thinned to a uniform density in the case of mungbean. Sheltered and open treatments remained unchanged from sowing through to harvest.

Crop measurements

Table 1 shows the dates when above-ground biomass, leaf area, height and grain yield measurements were taken at each site.

Esperance. Every year, the time taken for the crop to reach 50% emergence, anthesis and maturity was determined from counts within marked subplots in each treatment replicate. In 1995, 3 quadrats of 1 m^2 were used; in 1996, 1 m long sections of row in 3 quadrats were used and in 1997, 2 sections of 1 m of row in 3 quadrats were used in each treatment replicate. The density of wheat tillers (tillers/m^2) was determined just before stem elongation and head density (heads/m^2) was determined at harvest in the marked areas of crop. In 1997, anthesis and maturity dates, and head density were determined in the single non-waterlogged treatment replicates sheltered throughout the growing season.

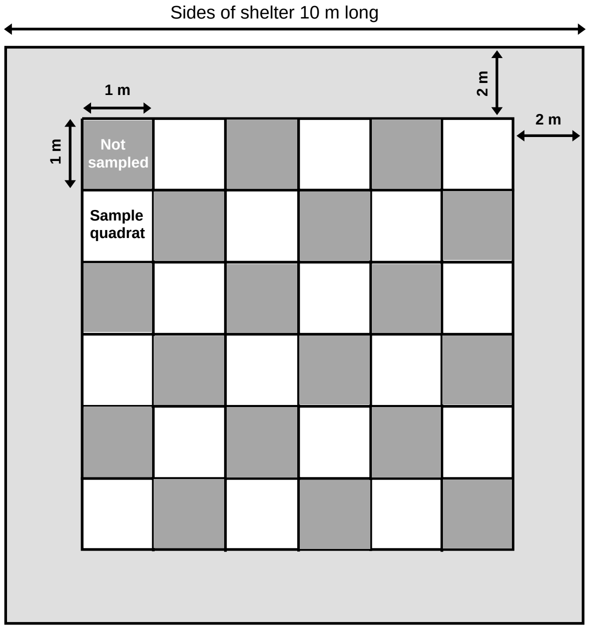

Figure 2. Plan view of shelter showing sampling grid and layout of measurement quadrats.

To determine above-ground biomass, samples were collected from 3 quadrats of 0.9 m^2 in each treatment replicate. The height, green leaf area and specific leaf area (the ratio of leaf area to leaf weight) of 2 median plants from each sample were determined using a Delta T Devices area meter (no model number) in 1995 and 1996 and a LiCor 3100 area meter in 1997.

At physiological maturity, 5 quadrats of 0.9 m^2 were harvested in each treatment replicate in 1995 and 4 in 1996 and 1997. Plant number, above-ground dry biomass, seed yield, 1000-seed weight and number of grains affected by black point were then determined. Black point is identified as a discolouration of the wheat grain, and can reduce grain quality and market value (Anderson and Garlinge 2000).

Dookie and Rutherglen. To determine above-ground biomass and grain yield, 3 samples of 1 m^2 were collected from each treatment replicate at each sampling time in both years. In 1997, leaf area was measured using a Paton Electronic Planimeter and specific leaf area was determined. Plant density was assessed on 23 May 1997 and tiller density was determined on 14 July 1997. The density of heads, seed yield and 1000-seed weight were determined at maturity.

Warwick. To determine above-ground biomass and grain yield, 3 samples of 1 m^2 were collected from each treatment replicate in 1997 and 3 samples of 0.4 m^2 in 1998. Leaf area was determined using a Delta T Mk2 leaf area meter. At maturity, seed yield was determined.

Soil water content

Table 1 lists the dates when soil water measurements were made. At Esperance, soil samples were taken at 0.1-m intervals down to 0.5 m using a 50 mm diameter auger. Samples were obtained from 3 auger holes in each treatment replicate and combined to give a single bulked sample in each treatment replicate for each depth interval. Each bulked sample was weighed then dried at 110°C for 48 h and re-weighed to determine gravimetric soil water content. Volumetric water content was estimated using soil bulk densities for a similar soil type published in Overheu *et al*. (1993). At Rutherglen, a neutron moisture meter access tube was installed in the centre of each treatment replicate. During the 1997 growing season, fortnightly measurements were taken at 0.2-m depth intervals down to a depth of 1.8 m. Soil water content was not determined at the Dookie and Warwick sites.

Meteorological measurements

Ambient wind speed at Esperance and Rutherglen was measured using Campbell Scientific Met-One 014A cup anemometers and recorded using a Datataker DT50 data logger. Measurements were made at Warwick using a RM Young wind sentry anemometer and recorded using a Campbell CR10 logger. Sensor height was 3 m at Esperance and 2 m at Rutherglen and Warwick, measurements were made automatically every 5 s and hourly averages recorded.

At Esperance in 1996 and 1997, Rutherglen in 1997 and Warwick in 1997, air temperature and relative humidity were measured 0.2 m above the crop canopy in a single open and sheltered treatment using aspirated Vaisala Humitter 50Y temperature and relative humidity sensors. Data from these sensors were recorded every 5 min on Datataker DT5 loggers and hourly averages calculated later. Before sowing, the instruments at each site were run together and cross-calibrated.

The following additional measurements were made:

Esperance. Wind speed was measured 0.2 m above the crop canopy in a single open and sheltered treatment throughout the growing season each year using Unidata cup anemometers, and Unidata PDL data loggers. Temperature and humidity were also measured 0.2 m above the crop canopy in an open and a sheltered treatment throughout the 1996 and 1997 growing seasons using Unidata LM34 temperature sensors and capacitive relative humidity sensors. Temperature and humidity sensors were housed in 126 mm diameter gill radiation shields.

Measurements were made every 5 s and hourly averages recorded using Unidata PDL data loggers. As reduced ventilation of the sheltered gill radiation shield may have allowed the shield to retain heat, data from the aspirated sensors have been used in preference to the data from the Unidata instruments where they are available.

In 1996 and 1997, soil temperature was measured 50 mm below the surface using 8 Unidata thermistor probes in a sheltered and an open treatment. Temperatures were measured every 5 s and hourly averages recorded using Unidata PDL data loggers.

Warwick. Wind speed inside and outside of a shelter was measured over 10 days in April 1997 using cup anemometers (made by CSIRO Division of Water and Soil, Canberra) installed 0.15 m above the mungbean crop.

Data analysis

Differences in crop growth between treatments were compared using an analysis of variance and regression analysis for the 1997 Esperance crop data. Soil water content data from Esperance were compared using analysis of variance with the water content at sowing as a covariate. The differences are considered significant at $P<0.05$. As meteorological measurements were not replicated they were not compared statistically.

Results

Microclimate

Wind speed. Mean wind speed (measured at 2 or 3 m) over the winter cropping seasons was 3.5 m/s in 1995 and 1997 and 4.1 m/s in 1996 at Esperance, 2.0 m/s at Dookie, 1.9 m/s at Rutherglen and 1.7 m/s at Warwick (Table 2). At Warwick over the 1997 and 1998 summer cropping seasons, wind speed averaged 2.0 m/s. Diurnal wind-speed trends (mean hourly values over all the days in each month) were relatively constant throughout the year at Warwick and over the winter cropping season at Rutherglen (Fig. 3). At Dookie, mean wind speed increased as the growing season progressed, and was greatest in September (data not presented). At Esperance, mean wind speed was least in early spring (September–October).

The reduction in wind speed (measured 0.2 m above the crop canopy) inside the shelters was similar at Esperance and Warwick (Fig. 4). Mean wind speed inside the shelters at Esperance was about 30% of open wind speed early in the growing season each year, and increased to about 40% of open wind speed at the end of the growing season. The reduction in wind speed was unaffected by open wind speed (Fig. 4); consequently, mean hourly wind speed inside the shelters was less than 1.5 m/s for most of the growing season at Esperance (Fig. 5).

Air temperature and humidity. Over the winter and summer cropping seasons at Esperance, Rutherglen and Warwick, mean air temperature, atmospheric vapour pressure (e_a) and vapour pressure deficit (VPD) inside the shelters were generally similar to conditions outside the shelters (Table 2). There were no data available for October at Rutherglen or for June–October at Warwick. During the winter months (June–August) temperatures were generally less at Rutherglen than at Howick, while spring temperatures were greater at Rutherglen (Fig. 6). Warm, dry conditions at the Rutherglen site at the end of the growing season meant maximum VPD was double that recorded at the Esperance and Warwick sites during November (Fig. 7).

While mean air temperature and VPD were largely unchanged in shelter over the winter cropping seasons at Esperance and Rutherglen (Table 2), warmer days and generally cooler nights inside the shelters increased the diurnal temperature (Fig. 8) and VPD (Fig. 9) ranges. Mean maximum daily temperature inside the shelters was increased by 0.3°C in 1996, and 0.9°C in 1997 at Esperance, and 0.5°C at Rutherglen (Table 2). The greatest increases in daily maxima in the shelters at Esperance were 2.4°C in November 1996 and 3.1°C in November 1997; at Rutherglen the greatest increase in daily maximum temperature was 3.0°C in November. Mean daily minimum temperature was increased by 0.1°C in 1996 at Esperance and decreased by 0.1°C at Esperance and Rutherglen in 1997. At Rutherglen

Table 2. Mean and maximum wind speed (at 3 m at Esperance and 2 m at other sites), air temperature, atmospheric vapour pressure and vapour pressure deficit (VPD) (0.15 m above crop canopy) during the winter growing seasons at Esperance (1995–97), Rutherglen (1997) and Warwick (1997) and summer growing seasons at Warwick (1997 and 1998)

Values in parentheses are maximum values over growing season

Meteorological parameter	Esperance			Dookie	Rutherglen	Warwick		
	1995	1996	1997	1996	1997	Winter 1997	Summer 1997	Summer 1998
Open wind speed (m/s)	3.5 (12.9)	4.1 (12.8)	3.5 (11.8)	2.0	1.9 (9.3)	1.7 (10.6)	2.0 (9.7)	2.0
Open air temperature (°C)	—	13.8	12.8	—	9.6	13.0	20.4	21.8
Sheltered air temperature (°C)	—	13.8	13.0	—	9.5	—	20.6	—
Open daily maximum air temperature (°C)	—	20.9 (43.2)	19.8 (40.3)	—	18.0 (45.3)	20.4 (33.8)	28.8 (37.5)	28.1 (36.0)
Sheltered daily maximum air temperature °C)	—	21.2 (44.8)	20.7 (41.8)	—	18.5 (46.8)	—	29.2 (40.7)	—
Open atmospheric vapour pressure (mb)	—	12.1	12.3	—	10.1	—	16.8	—
Sheltered atmospheric vapour pressure (mb)	—	12.4	12.6	—	10.0	—	17.2	—
Open VPD (mb)	—	4.3	2.9	—	3.4	—	7.7	—
Sheltered VPD (mb)	—	4.0	2.9	—	3.5	—	7.4	—
Open maximum VPD (mb)	—	12.3 (73.7)	9.1 (54.5)	—	11.2 (94.6)	—	21.2	—
Sheltered maximum VPD (mb)	—	11.8 (75.8)	9.4 (57.4)	—	11.8 (102.5)	—	21.4	—

and Esperance, VPD was largely unchanged or was less inside the shelters than outside between June and September, at Esperance the greatest reduction in VPD occurred around noon when maximum VPD was recorded (Fig. 9). However, in late winter–spring (September–November), VPD was increased inside the shelters around noon at Rutherglen, Esperance and Warwick.

At Warwick over the summer cropping season, warmer nights and reduced daily maxima decreased the diurnal air temperature (Fig. 8) and VPD range (Fig. 9). Consequently, the mean minimum temperature was 0.5°C higher and the mean maximum temperature 0.3°C lower inside the shelters, while VPD was generally less inside the shelters than outside.

Soil temperature. At Esperance in 1996, soil temperature inside the shelter was generally less in the morning and early afternoon than outside and greater in the evening until October, after which the sheltered soil was generally cooler than the unsheltered soil (Fig. 10*a*). In 1997, the sheltered soil was generally warmer than the unsheltered soil (Fig. 10*b*).

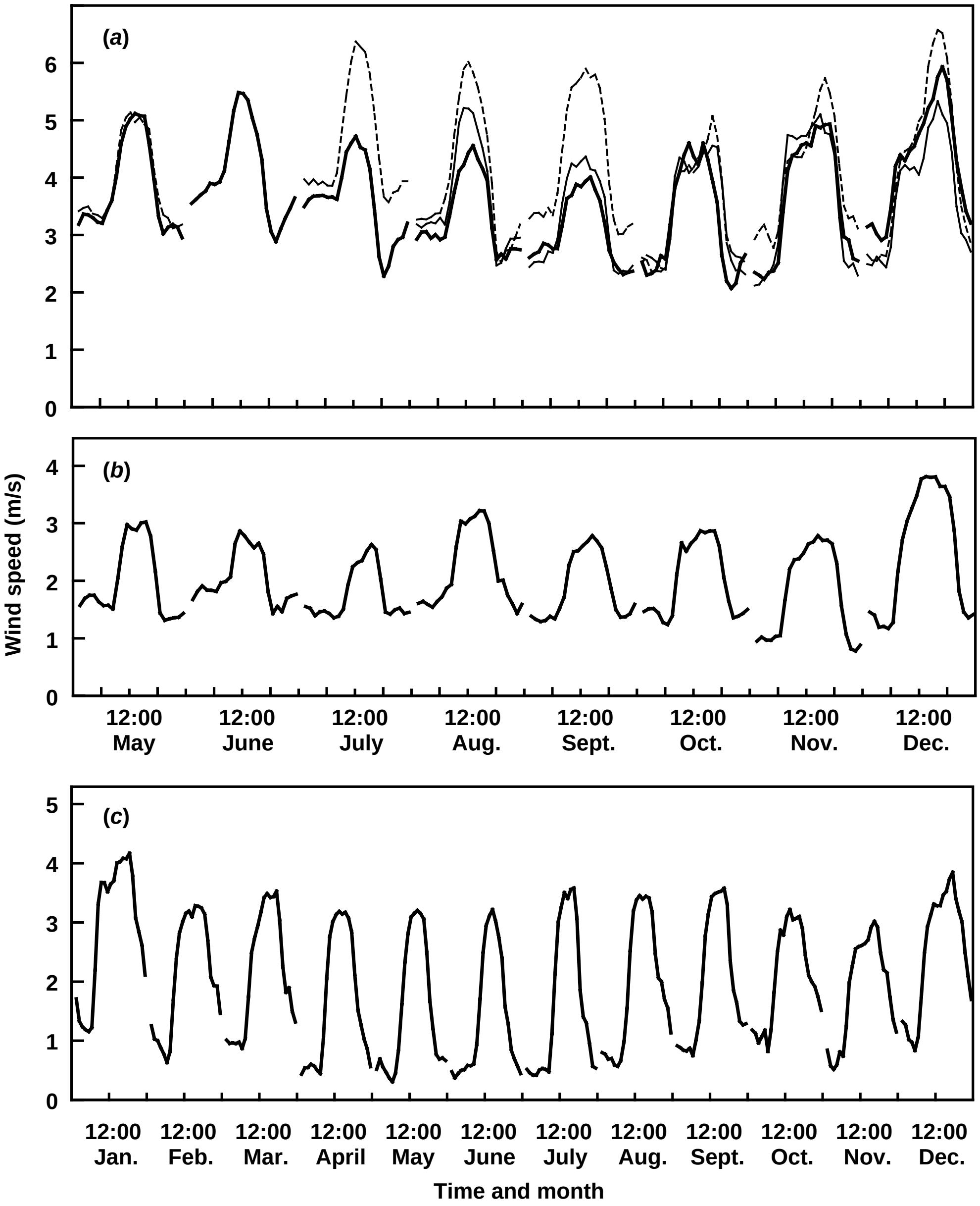

Figure 3. Trends in diurnal wind speed (mean hourly values over all the days in each month): (*a*) 3 m above the ground surface at Esperance, 1995 (—), 1996 (- - -) and 1997 (——); (*b*) 2 m above the ground surface at Rutherglen 1997; and (*c*) 2 m above the ground surface at Warwick 1997.

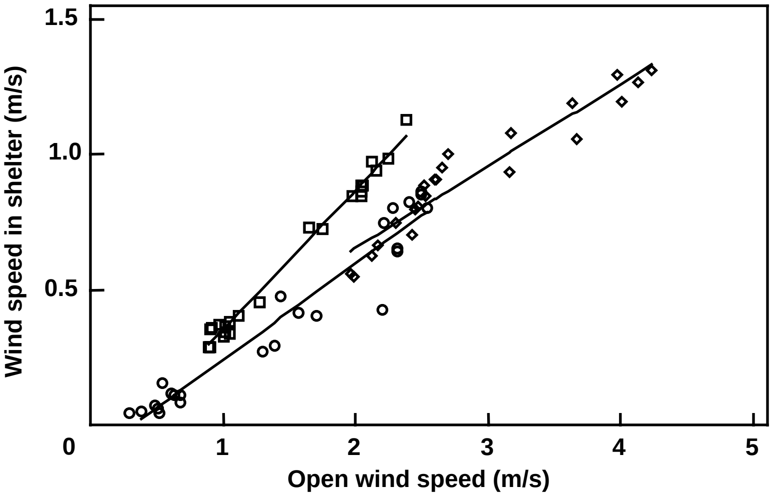

Figure 4. Mean hourly wind speed 0.15 m above the crop canopy inside and outside a shelter at Esperance in July (◇) and October (□) 1996 and Warwick (○) in April 1997. Also shown are trend lines for open *v.* sheltered wind speed in July [sheltered wind speed = 0.30 (open wind speed) + 0.05, $r^2 = 0.91$] and October [sheltered wind speed = 0.52 (open wind speed) – 0.16, $r^2 = 0.99$] at Esperance and April [sheltered wind speed = 0.36 (open wind speed) – 0.12, $r^2 = 0.93$] at Warwick.

Soil water content

At the Esperance and Rutherglen sites, differences in soil water content inside and outside of the shelters were never significant, although soil water content was consistently greater inside the shelters after crops were established (Fig. 11).

Above-average rainfall at the Esperance site in 1997 caused severe waterlogging from the time the crop began tillering until after anthesis, with water ponding on the soil surface during August and September. Above-average rainfall at Dookie in 1996 also caused waterlogging, with water ponding on the surface for about 2 weeks in late July–early August.

Crop phenology and growth

Phenology. Sheltered and unsheltered plants emerged, flowered and matured at a similar rate at Esperance (data not presented).

Establishment, *morphology and growth.* At Esperance, sheltered and unsheltered crops emerged at similar densities in 1997 and 1995. In 1996, sheltered wheat established at a higher density than unsheltered wheat (233 plants/m^2

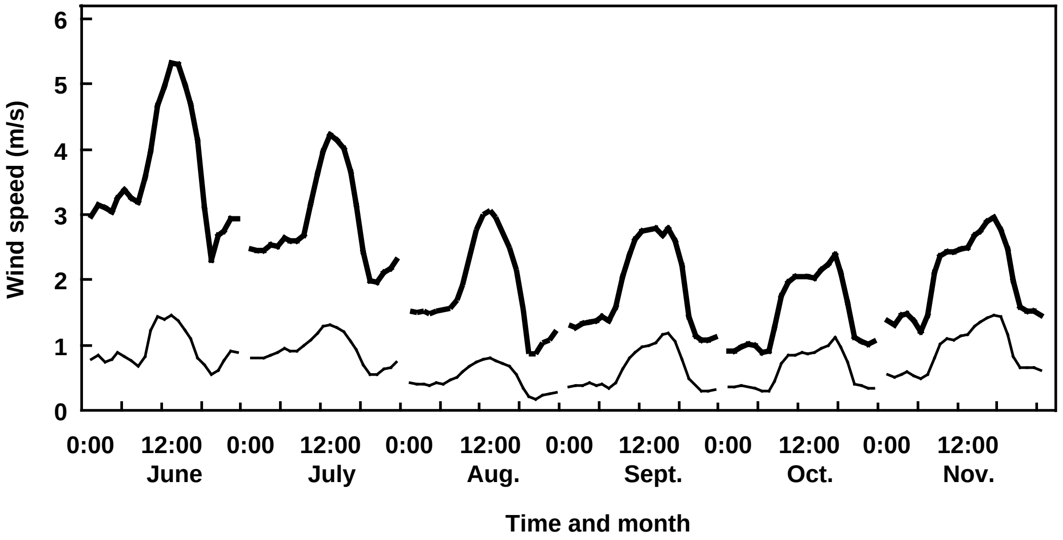

Figure 5. Trends in wind speed (mean hourly values over all the days in each month) 0.15 m above the crop canopy inside (thin line) and outside (thick line) of shelters each month during the growing season at Esperance in 1996.

compared to 176 plants/m^2, $P<0.05$). Subsequently, the number of tillers/m^2 was similar inside and outside the shelters, but the sheltered wheat developed significantly ($P<0.01$) more heads than the unsheltered (350 heads/m^2 compared to 264 heads/m^2). At Rutherglen and Warwick, the density of wheat tillers was similar inside and outside the shelters and at Rutherglen, sheltered and unsheltered wheat had a similar number of heads/m^2.

At the Esperance site, the sheltered plants were taller than unsheltered plants in 1995 and 1996 (Table 3). In 1995, sheltered lupins were 130 mm (25%) taller at maximum leaf area. In 1996, sheltered wheat was 60 mm (20%) taller at the start of stem elongation and 60 mm (8%) taller at physiological maturity ($P<0.05$). Height differences in 1997 were not significant. However, at physiological maturity sheltered wheat was 70 mm (11%) taller despite being

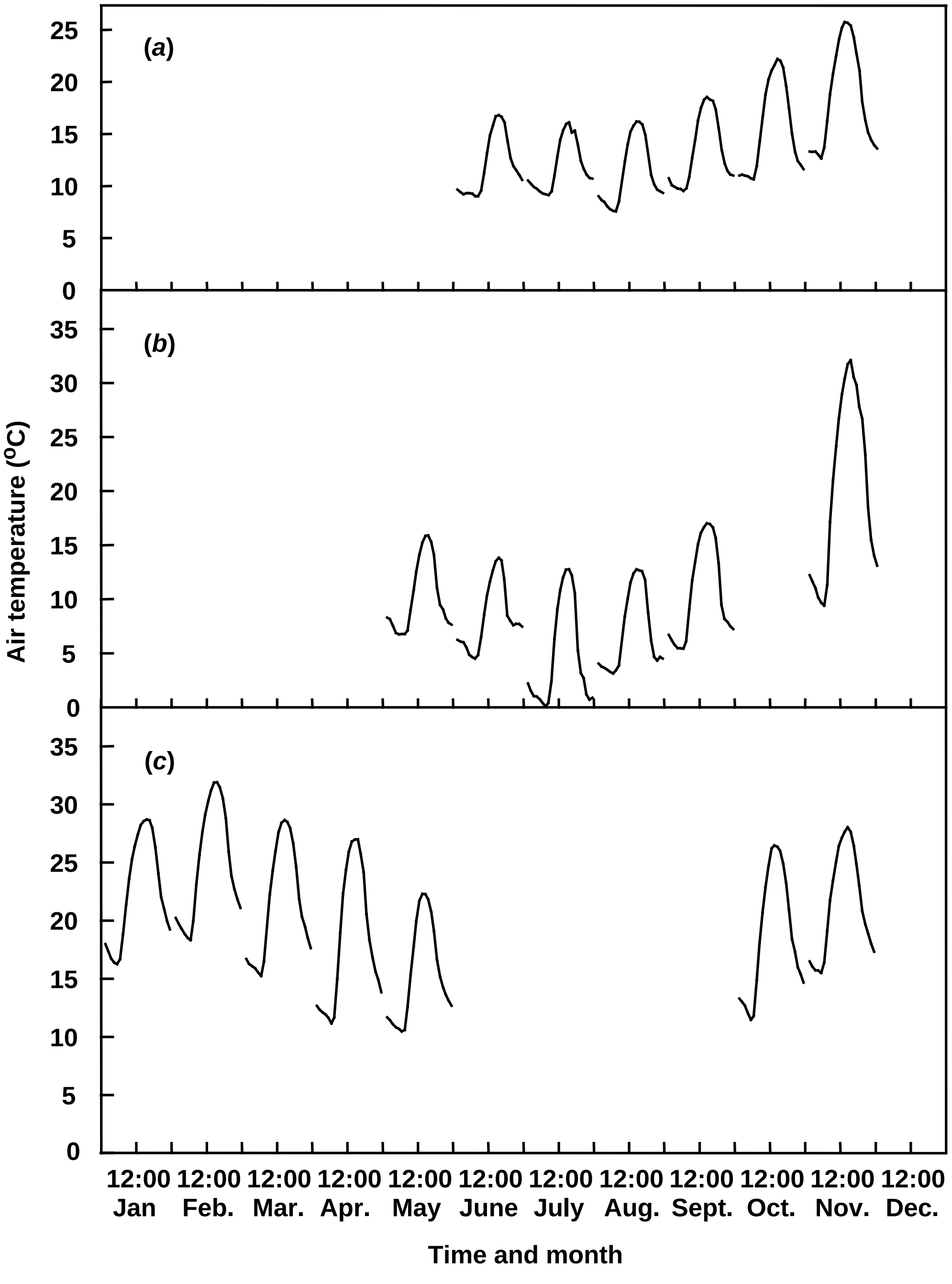

Figure 6. Trends in diurnal air temperature (mean hourly values over all the days in each month) 0.15 m above the crop canopy outside of the shelters at (*a*) Esperance in 1996, (*b*) Rutherglen in 1997 and (*c*) Warwick in 1997.

similar in height to unsheltered wheat at ear emergence. The height of sheltered and unsheltered wheat at Warwick was similar (data not presented). Plant height was not determined at Dookie and Rutherglen.

Except for wheat crops at Esperance in 1997 and Dookie in 1996, which were waterlogged, sheltered crops consistently developed more above-ground biomass (Fig. 12) and/or leaf area (Table 4) than unsheltered crops. However, increases in above-ground biomass were only statistically significant at Esperance in 1995 (up to 68% greater) and 1996 (up to 48% greater) and sheltered leaf area was only significantly greater than unsheltered leaf area at Esperance in 1995 (up to 111% greater) and 1996 (up to 42% greater). Increased leaf area and above-ground biomass were associated with decreased structural tissue in the plants as indicated by greater specific leaf area and/or ratio of leaf area to total above-ground biomass in the shelters (Table 4). These increases were significant in 1995 and 1996 at the Esperance site and in 1997 for the wheat and mungbean crops at Warwick. Maximum leaf area index inside and outside of the shelters at Esperance was 4.2 and 3.4, respectively, in 1995, 2.6 and 1.7 in 1996 and 1.1 and 1.3 in

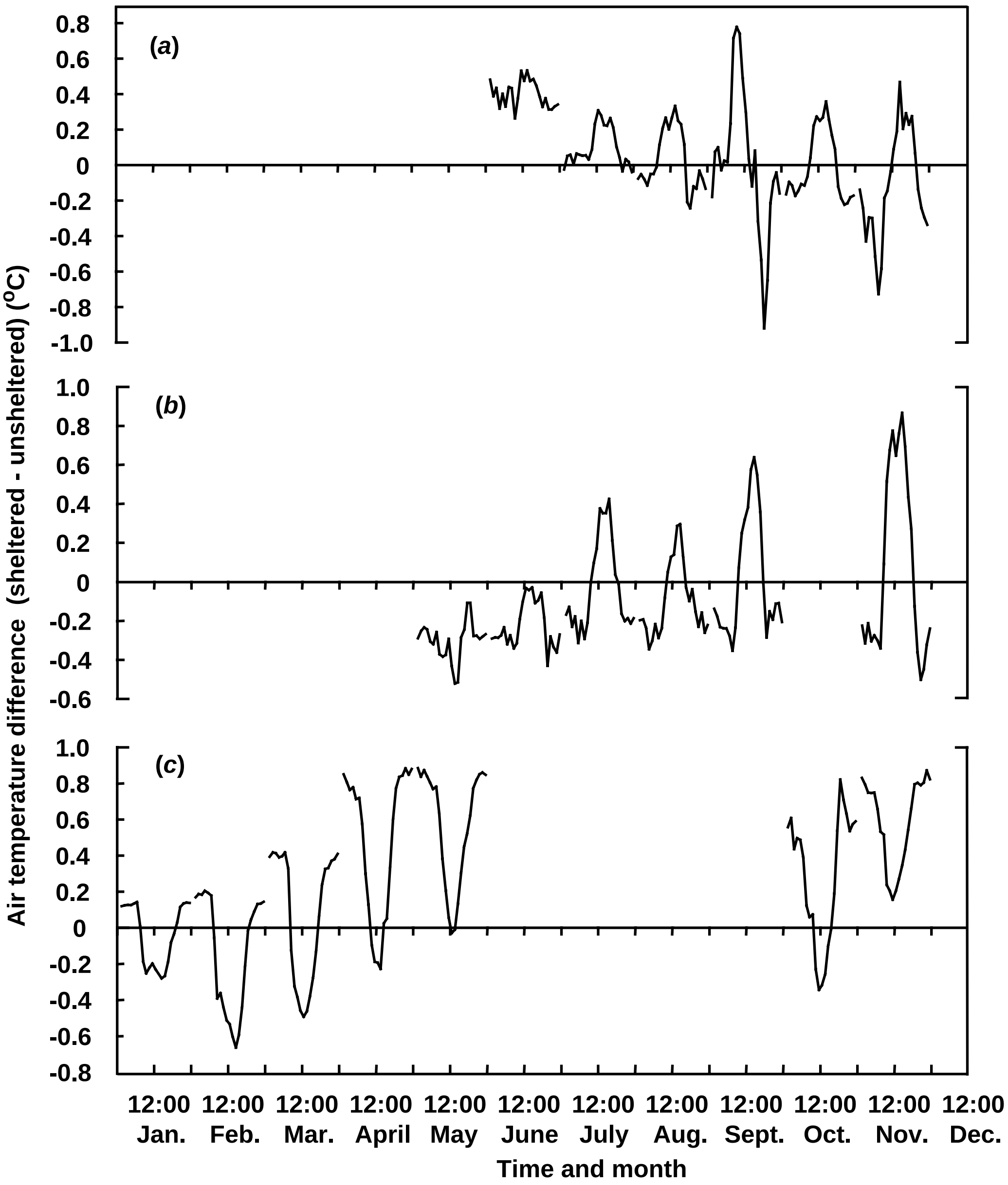

Figure 7. Difference between air temperature (mean hourly values over all the days in each month) measured 0.15 m above the crop canopy inside and outside shelters at (*a*) Esperance in 1996, (*b*) Rutherglen in 1997 and (*c*) Warwick in 1997.

1997. Maximum leaf area index was 4.9 inside the shelters and 4.1 outside at Rutherglen. At Warwick, the maximum leaf area index of mungbeans in 1997 was 2.5 inside the shelters and 1.7 outside, for wheat in 1997 the leaf area index was 1.6 inside the shelters and 1.4 outside and for mungbeans in 1998 it was 1.2 inside and 1.0 outside.

When soils were waterlogged after establishment at Esperance in 1997, and after stem elongation at Dookie in 1996, the sheltered plants developed less above-ground biomass (significantly for wheat at harvest at Esperance in 1997, Fig. 12) and leaf area, and had reduced specific leaf area and ratios of leaf area to above-ground biomass, compared to unsheltered crops (Table 4, Fig. 12). The severity of waterlogging varied across the trial sites, which increased the variability of crop growth characteristics.

Inside the shelters, the grain yield of wheat at Esperance in 1996 was increased by 20% ($P<0.05$) and the yield of mungbeans at Warwick in 1997 was increased by 12% ($P<0.05$). However, the yield of wheat affected by waterlogging at Esperance in 1997 decreased by 22% ($P<0.05$). At other sites and years, yield inside and outside the shelters was similar (Table 5). The harvest index and 1000-grain weight of non-waterlogged crops was not affected by shelter (data not presented). Significantly more wheat grains were affected by black point in the shelters at Esperance in 1996 and 1997 (Table 5).

Discussion

The reductions in wind speed achieved inside the artificial shelters in this study were much greater than those likely in

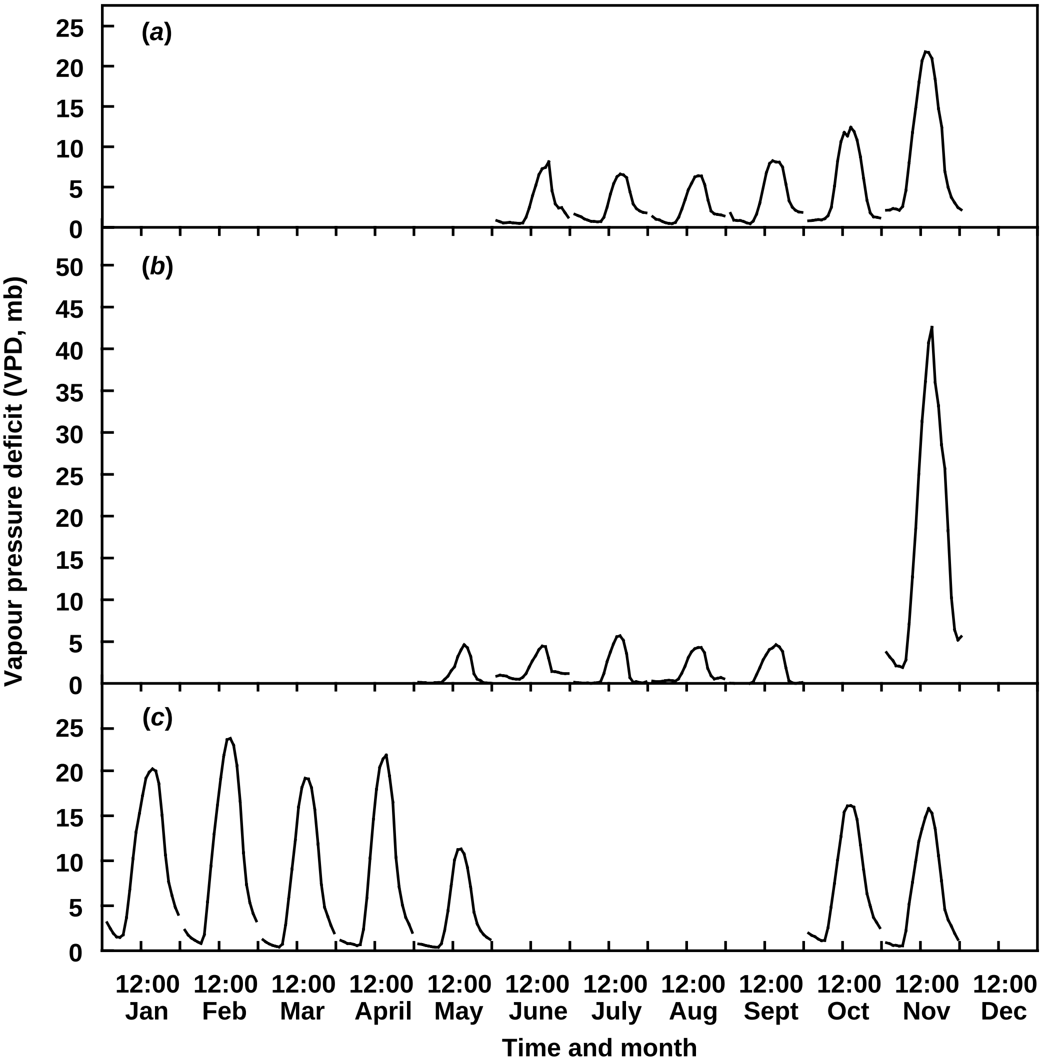

Figure 8. Trends in diurnal vapour pressure deficit (VPD) (mean hourly values over all the days in each month) 0.15 m above the crop canopy outside of the shelters at (*a*) Esperance in 1996, (*b*) Rutherglen in 1997 and (*c*) Warwick in 1997.

conventional tree windbreak systems. Subsequent crop growth clearly illustrates that microclimate modification at this level can be both beneficial and harmful. Grain yield in shelter ranged between 78 and 120% of unsheltered yield, depending on seasonal conditions and crop species. The mean yield for all sites, crops and years was 99% of unsheltered yield. These data for crops growing in more sheltered environments than will commonly be achieved in tree windbreak systems provide benchmarks within which most of the field and modelled data of the NWP fall.

The artificial shelters at Esperance and Warwick provided similar reductions in wind speed (Fig. 4). Over 3 growing seasons at Esperance, the shelters consistently reduced wind speed by 60–70% (Fig. 5). There was a slight decrease in the effectiveness of the shelters during the growing season at Esperance (Fig. 4). This may have been due to the ratio of wind-speed measurement height to shelter height increasing as the crops grew, from 0.2 at the start of the growing season to 0.5 at the end of the growing season. As the growing season progressed, this effectively moved the anemometer nearer the top of the shelter where the air stream was more turbulent and wind speed less reduced than lower in the shelters (Heisler and DeWalle 1988). Reductions in wind speed of 70% are similar to those found within 3 times the height (H) of dense tree windbreaks when the wind is perpendicular to the windbreak (Cleugh and Hughes 2002). However, these wind-speed reductions are greater than could be expected in tree windbreak systems where changing wind direction throughout the growing season reduces the overall effectiveness of the windbreaks (Sudmeyer and Scott 2002*a*). Therefore, the experiment achieved its goal of providing higher levels of shelter than is common with field

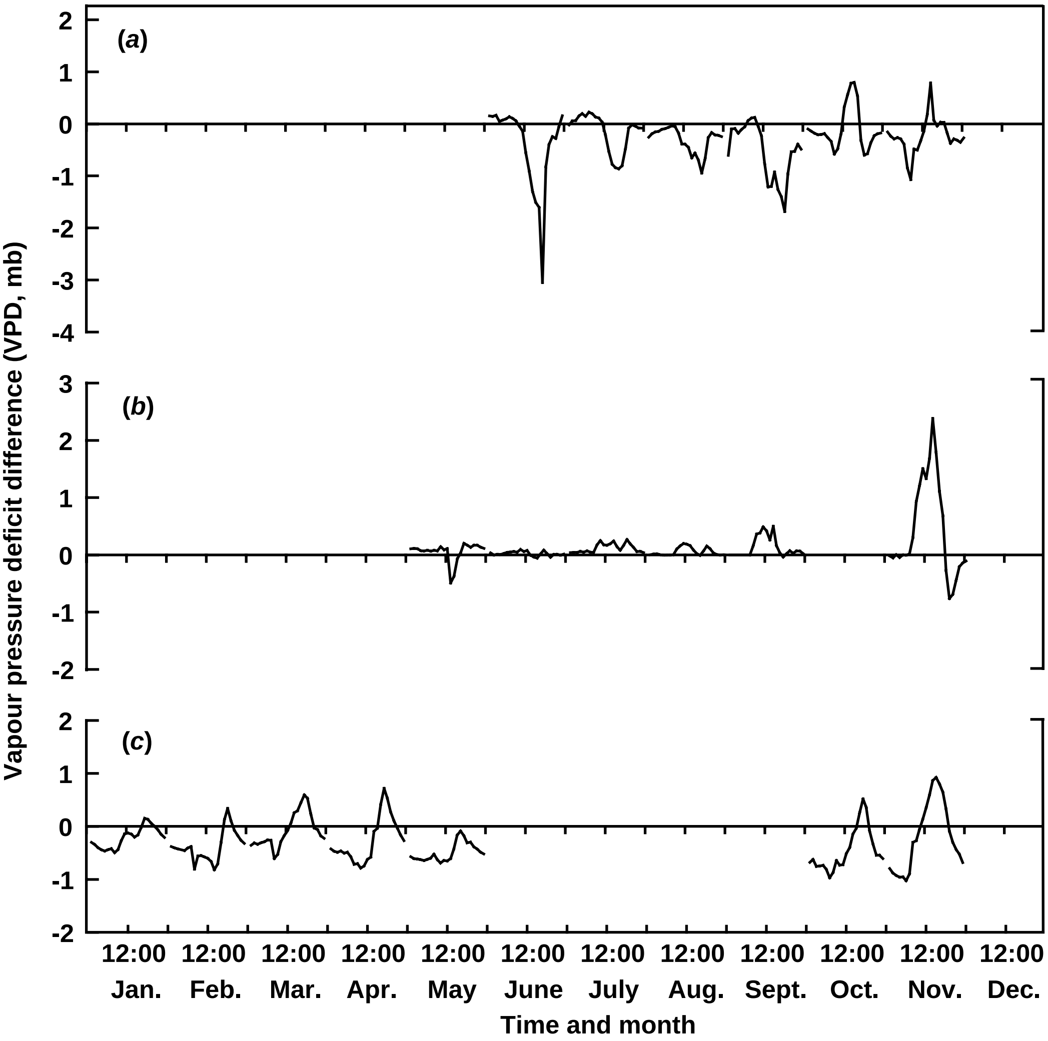

Figure 9. Difference between vapour pressure deficit (VPD) (mean hourly values over all the days in each month) measured 0.15 m above the crop canopy inside and outside shelters at (*a*) Esperance in 1996, (*b*) Rutherglen in 1997 and (*c*) Warwick in 1997.

windbreaks, in order to benchmark the maximum microclimate and crop growth and development changes possible.

The magnitude of temperature and humidity changes inside the shelters in this study were similar to those measured within 6 H of tree windbreak systems when the wind is at right angles to the windbreak (e.g. Burke 1991; Casa *et al*. 1993; Kaisin 1993; Cleugh and Hughes 2002; Sudmeyer and Scott 2002*a*). Mean air temperature and humidity over the growing season were largely similar inside and outside the shelters at the 3 sites (Table 2). The small change in mean air temperature in the shelters did not affect development rates of crops grown at Esperance. However, in tree windbreak systems the effect of shelter on crop phenology at 3–10 H appears to be variable. The phenology of sheltered and unsheltered canola (*Brassica napus*), barley (*Hordeum vulgare*) and lupin was similar at another Western Australian site (Sudmeyer and Scott 2002*b*), as was canola at a South Australian site (Nuberg *et al*. 2002), but sheltered wheat at the South Australian site flowered earlier.

While mean air temperature and humidity were largely similar inside and outside the shelters, there were clear diurnal differences between microclimate inside and outside the shelters at Esperance and Rutherglen. Greater daily maxima during the winter growing seasons increased the diurnal temperature range in the shelters, particularly in October and November (Fig. 7). The maximum temperature increases inside the shelters at Rutherglen and Esperance (2.4–3.1°C) were greater than the 1.4°C increase reported by Cleugh and Hughes (2002) for a dense windbreak in a wind tunnel. At Esperance, air and soil temperatures were generally greater in shelter when LAI was less inside the shelter compared to outside, however when LAI was increased in the shelter, soil temperature was less than in the open (Table 2, Figs 8 and 9).

Shelter resulted in lower mean VPD values during summer at Warwick, and for most of the winter growing season at Esperance, but VPD remained largely unchanged or even increased slightly at Rutherglen. However, maximum VPD was increased in the shelters at the end of the winter growing season at all 3 sites. Using a process-based model, Cleugh (2002) estimated that transpiration from the crops in the shelters was reduced by between 7 and 8% at Esperance (in 1996), Rutherglen and Warwick. Cleugh (2002) also

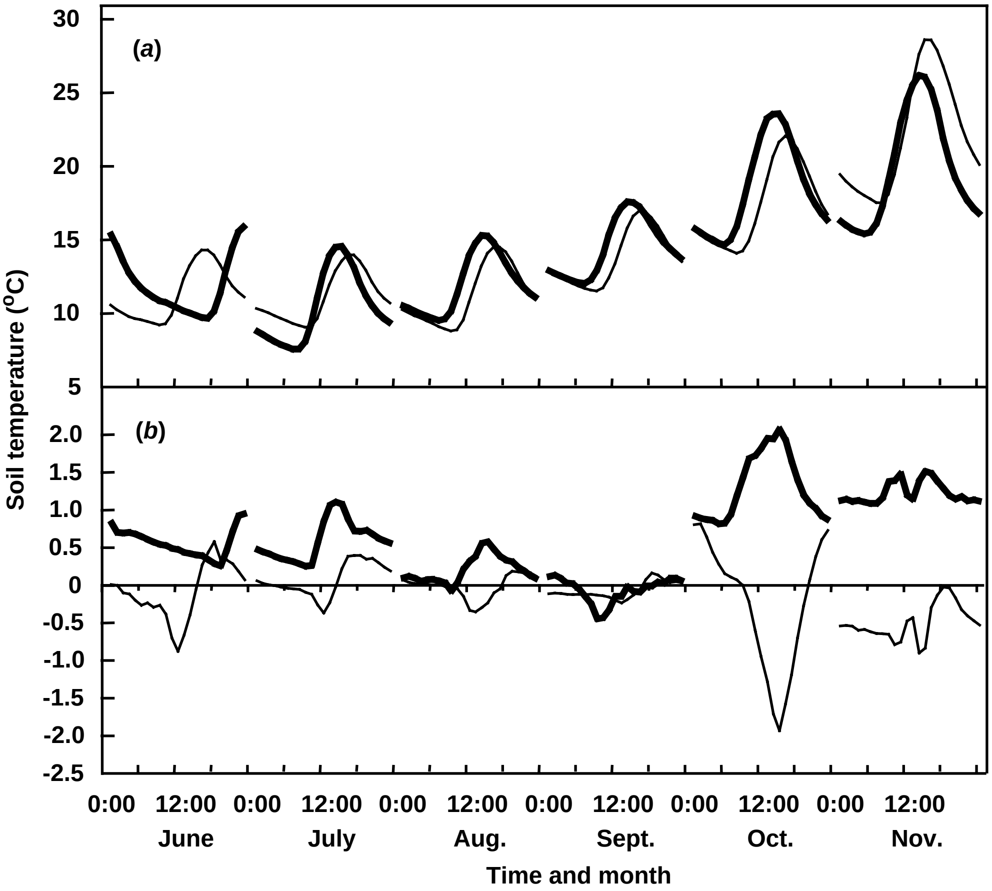

Figure 10. Trends in diurnal soil temperature (50 mm deep) (mean hourly values over all the days in each month) (*a*) inside of a shelter and (*b*) difference in soil temperature in shelter compared to open field in 1996 (thin line) and 1997 (thick line) at Esperance.

showed that shelter had most effect in reducing evaporation of soil water (25% reduction at Rutherglen). For tree windbreak systems, the estimated changes in evaporative demand were smaller; the reduction in transpiration from crops 3–6 H from a tree windbreak at Esperance was estimated to be 2–3%.

Under water-limited conditions, reduced soil evaporation and crop transpiration benefit sheltered plants by delaying water stress and increasing leaf water potential and turgor pressure (Grace and Russell 1982; Rosenburg *et al.* 1983; Cleugh 1998). Reduced physical movement of plants and improved plant water relations can give sheltered plants increased opportunity for photosynthetic activity, extension of cell walls and growth of leaf area (e.g. Russell and Grace 1978; Ogbuehi and Brandle 1982; Biddington 1986; Hough and Cooper 1988; Johjima *et al.* 1992). In Australia, it is likely that reduced physical wind damage of crops is also a primary benefit of shelter (Cleugh 1998; Nuberg 1998).

In this study, where the unsheltered crops did not show any visible physical damage, wind speed and microclimate changes inside the shelters had both positive and negative effects on the morphology and above-ground biomass growth of sheltered lupins, mungbeans and wheat, depending on rainfall during the growing season (Tables 3, 4 and 6). When growing season rainfall was average or below average, sheltered crops at all of the sites tended to develop more leaf area than unsheltered crops. Increased leaf area was associated with a decrease in the amount of above-ground biomass partitioned to structural tissue, i.e. the specific leaf area and ratio of total above-ground biomass to leaf area was greater inside the shelters (Table 4). At the Esperance site, which was the windiest site, sheltered plants

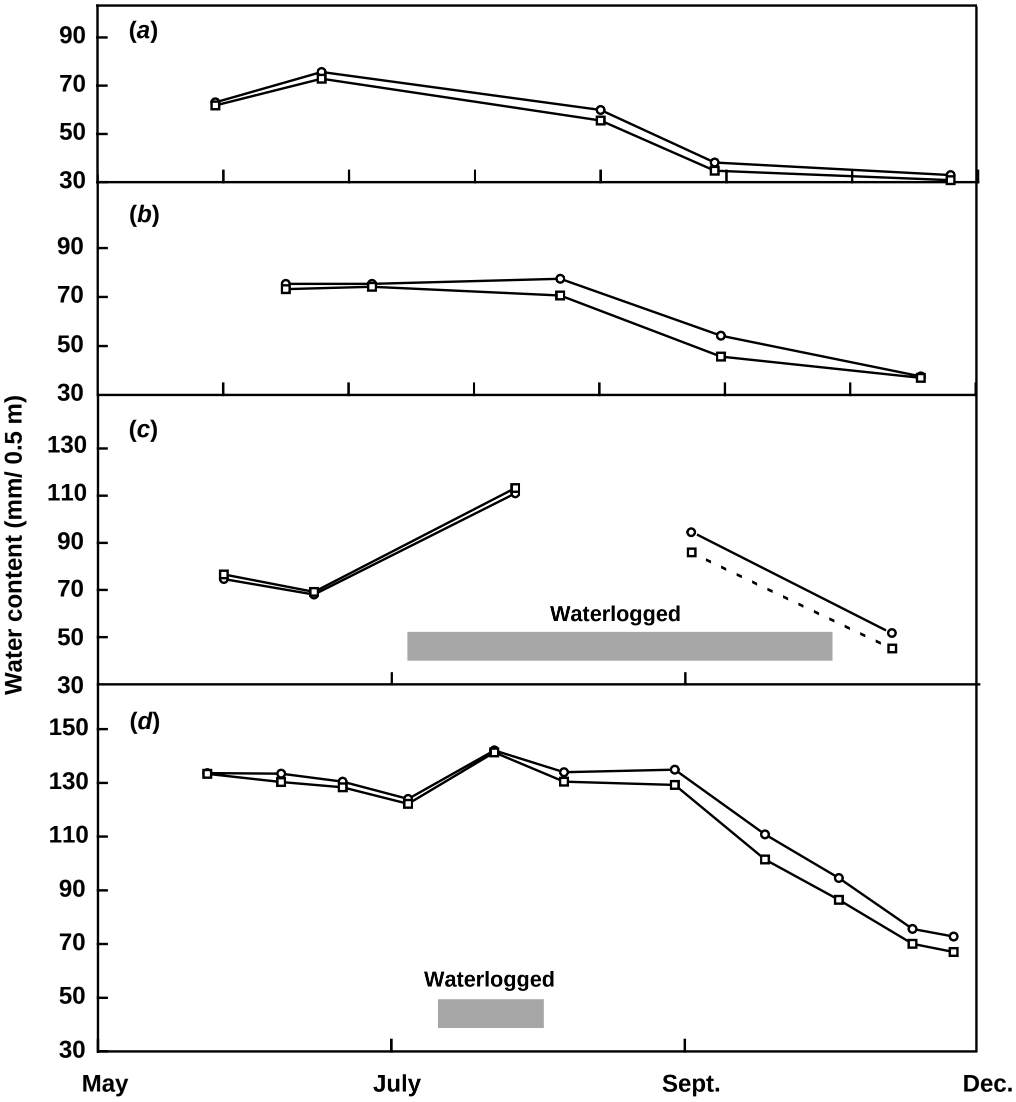

Figure 11. Stored soil water (0–0.5 m) inside (○) and outside (□) shelters at Esperance in (*a*) 1995, (*b*) 1996, (*c*) 1997 (solid lines are sowing to anthesis; dashed lines are anthesis to harvest) and (*d*) at Rutherglen in 1997.

Table 3. Sheltered and unsheltered plant height (mm) at Esperance (1995–97)

Crop developmental stage	1995 lupins		1996 wheat		1997 wheat[AB]	
	Unsheltered	Sheltered	Unsheltered	Sheltered	Unsheltered	Sheltered
100% emergence	26	40***	123	133n.s.	89	95n.s.
Stem elongation	—	—	295	356*	291	271n.s.
100% anthesis	438	553***	759	805n.s.	—	—
End of anthesis (lupins), ear emergence (wheat)	612	763**	—	—	357, 367[C]	373n.s., 383[C]
Harvest	—	—	773	833*	737[C]	817[C]

[A] Crop was waterlogged for part of the growing season. [B] Means for 2 cultivars (Machette and Carnamah).
[C] Single treatment replicates measured from sowing to harvest.
n.s., not significant; *$P<0.05$; **$P<0.01$; ***$P<0.001$.

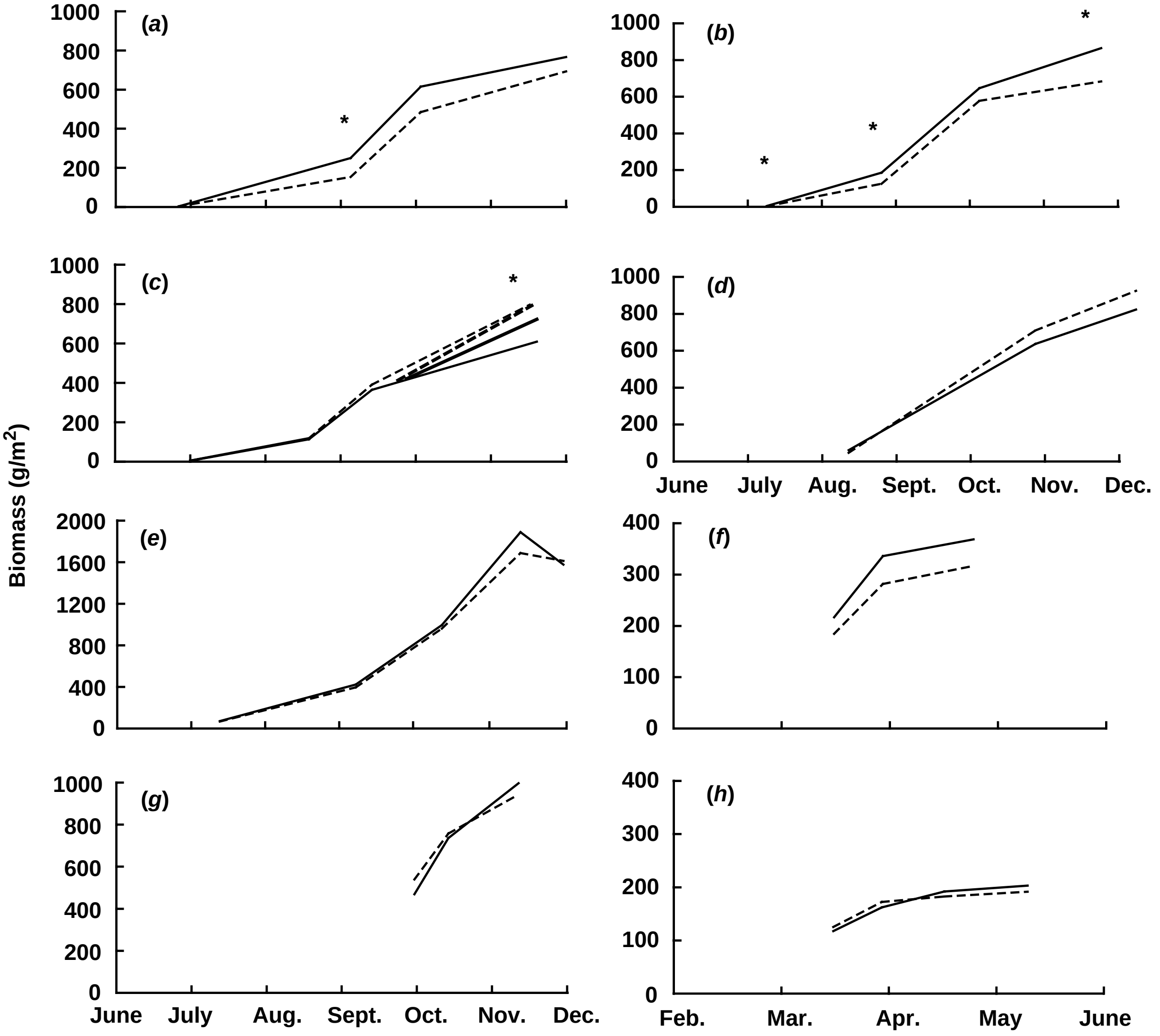

Figure 12. Above-ground biomass of sheltered (solid lines) and unsheltered (dashed lines) for (*a*) lupins in 1995, (*b*) wheat in 1996 and (*c*) wheat in 1997 at Esperance [values for crop measured from sowing to harvest are from single treatments and are not replicated, values from anthesis to harvest (thicker lines) are means of 3 replicates], and (*d*) wheat in 1996 at Dookie, (*e*) wheat in 1997 at Rutherglen, (*f*) mungbeans in 1997, (*g*) wheat in 1997 and (*h*) mungbeans in 1998 at Warwick. Significant differences between treatments are marked with an asterisk.

Table 4. Leaf area index (LAI), specific leaf area (SLA) and leaf area : above-ground biomass (LA : B) in shelter expressed as a percentage of unsheltered values, Esperance (1995–97), Rutherglen (1997) and Warwick (1997–98)

Crop and location	100% emergence			Early to mid-vegetative			Late vegetative–anthesis			End anthesis–start grain fill		
	LAI	SLA	(LA : B)	LAI	SLA	(LA : B)	LAI	SLA	(LA : B)	LAI	SLA	(LA : B)
Winter crops												
Lupins (Esperance, 1995)	211*	116*	119n.s.	—	—	—	174**	116*	105n.s.	123n.s.	111*	97n.s.
Wheat (Esperance, 1996)	142*	113n.s.	114n.s.	153n.s.	109n.s.	103n.s.	134*	104n.s.	119*	—	—	—
Wheat (Esperance, 1997)^{AB}	98n.s.	108n.s.	107n.s.	87n.s.	90n.s.	91*	84n.s.	89n.s.	94*	98n.s.	—	—
Wheat (Rutherglen, 1997)	—	—	—	120n.s.	103n.s.	113n.s.	—	—	—	—	—	—
Wheat (Warwick, 1997)	—	—	—	—	—	—	108n.s.	99n.s.	125n.s.	125n.s.	118n.s.	129*
Summer crops												
Mungbeans (Warwick, 1997)	—	—	—	—	—	—	103n.s.	85n.s.	121n.s.	106n.s.	130*	104n.s.
Mungbeans (Warwick, 1998)	—	—	—	101n.s.	96n.s.	107n.s.	111n.s.	102n.s.	107n.s.	113n.s.	94n.s.	108n.s.

^{A}Crop was waterlogged for part of the growing season.
^{B}Means for 2 cultivars (Machette and Carnamah).
*P<0.05; **P<0.01; n.s., not significant.

were also taller than unsheltered plants (Table 3). However, when rainfall was above average (Esperance in 1997 and Dookie in 1996), and the soil was waterlogged for part of the growing season, sheltered crops tended to have less above-ground biomass (Fig. 12) and, at Esperance, reduced LAI and grain yield (Tables 4 and 5). The growth of pasture in similar shelters has also been shown to decline relative to unsheltered pasture in waterlogged conditions (Bird *et al.* 2002*a*).

Reduced evaporative demand was probably the most important factor in altering crop growth in the shelters. At Esperance in 1995 and 1996 and Rutherglen in 1997, the sheltered crops were able to develop more leaf area (Fig. 12) without using more soil water (Fig. 11) than unsheltered crops. The crop water-use efficiency (grain yield/water use) was significantly improved at Esperance in 1996 and Warwick in 1997. Lynch *et al.* (1980) found similar improvements in the water-use efficiency of pasture growing inside artificial shelters in eastern Australia. Reduced wind speed and VPD in our shelters directly reduced evapotranspiration, particularly early in the growing season (Cleugh and Hughes 2002). Increased early vigour and earlier development of canopy cover inside the shelters at Esperance in 1996 (Fig. 12) shaded the soil and decreased soil temperature (Fig. 10), and may have decreased soil evaporation as a percentage of total evapotranspiration (Leuning *et al.* 1994; Simpson and Siddique 1994; Cleugh 1998). This can be particularly useful in the medium and low rainfall areas of Australia where soil evaporation can account for 40–60% of total evapotranspiration (Leuning *et al.* 1994; Yunusa *et al.* 1993; Simpson and Siddique 1994).

Early vigour of cereals has also been linked to increased rooting depth and increased grain yield potential (ear weight) at anthesis (Turner 1997). Reduced evaporation of soil water

Table 5. Grain yield, and percentage seeds affected by black point in sheltered and unsheltered crops at Esperance (1995–97), Dookie (1996), Rutherglen (1997) and Warwick (1997–98)

Crop and location	Grain yield (g/m^2)		Seeds with black point (%)	
	Unsheltered	Sheltered	Unsheltered	Sheltered
Winter crops				
Lupins (Esperance, 1995)	317	303n.s.	—	—
Wheat (Esperance, 1996)	296	355*	0.9	2.4**
Wheat (Rutherglen, 1997)	570	543n.s.	—	—
Wheat (Warwick, 1997)	395	414n.s.	—	—
Wheat (Esperance, 1997)^{AB}	238	186*	1.0	2.8**
Wheat (Esperance, 1997)^{AC}	245	178	1.35	3.65
Wheat (Dookie, 1996)^{A}	320	313n.s.	—	—
Summer crops				
Mungbeans (Warwick, 1997)	115	129*	—	—
Mungbeans (Warwick, 1998)	101	85n.s.	—	—

^{A}Crop was waterlogged for part of the growing season. ^{B}Sheltered from anthesis to harvest.
^{C}Single treatment replicates measured from sowing to harvest.
*P<0.05; **P<0.01; n.s., not significant.

from the sheltered treatments, and hence greater soil water content near the surface, may have contributed to greater plant density in shelter at Esperance in 1996 (which was comparatively dry at the start of the growing season) by improving seed germination and establishment. At Esperance in 1996, increased early wheat growth in shelter improved the yield potential of the wheat (both carbohydrate sources and sinks) by increasing plant density, LAI and ear and spikelet number (Anderson and Garlinge 2000). Increased grain yield of sheltered mungbean at Warwick (where shelters were erected after the crop had emerged and been thinned to a uniform density) clearly shows that shelter continued to benefit plant growth after establishment.

While the leaf area of non-waterlogged crops was consistently greater in shelter, there was no similar trend in grain yield, and only sheltered wheat at Esperance in 1996 and mungbeans at Warwick in 1997 yielded significantly more grain than the unsheltered crops. While there is no evidence of the sheltered crops at Rutherglen in 1997 and Esperance in 1995 depleting stored soil water at a greater rate than unsheltered crops, rainfall at both sites was below average when the lupin and wheat were filling grain. Nuberg and Mylius (2002) also found wheat grown in similar artificial shelters maintained greater leaf area than unsheltered wheat without depleting more stored soil water before anthesis; however, grain yield was not increased in shelter. Declining availability of soil water at a time when temperature and VPD were most increased in the shelters may have induced stomatal closure and reduced photosynthetic rates of sheltered plants (Turner *et al*. 1987). Also, increasing LAI beyond 3–4 (as was the case for lupins at Esperance and wheat at Rutherglen) does not always increase net photosynthesis (Evans *et al*. 1975; Leopold and Kriedemann 1975; Giunta *et al*. 1995). The sheltered lupins which developed more above-ground biomass before anthesis may also have experienced stronger competition for assimilates between developing branches, flowers and fruit later in the season than unsheltered plants with less above-ground biomass (Farrington and Pate 1981; Dracup and Kirby 1996). In fact, lupins subjected to a mild water deficit during anthesis may develop fewer ancillary branches, but yield more seed than lupins not subjected to a water deficit (Turner 1997). This result at Esperance is at odds with other Australian studies (Bicknell 1991; Sudmeyer *et al*. 2002) which have shown lupins to be generally more responsive to shelter than cereals, and probably reflects greater increases in lupin biomass in the shelters than is commonly achieved in tree windbreak systems. It also highlights the complexity of interactions between various environmental conditions in terms of their integrated effect on yield.

When soil was waterlogged (Esperance in 1997 and Rutherglen), the growth of sheltered plants was reduced throughout the growing season (Fig. 10), possibly because reduced evaporative demand inside the shelters extended the duration and severity of waterlogging and increased stresses on sheltered plants when potential yield was being set. At the end of the growing season, as waterlogging abated, sheltered plants at Esperance were also subjected to greater air and soil temperature increases than non-waterlogged sheltered plants. Another disadvantage of increased atmospheric vapour pressure and reduced VPD in the shelters was increased fungal staining (Anderson and Garlinge 2000) of the wheat grains inside shelters at the Esperance site.

Recent Australian field studies have shown that crop growth in tree windbreak systems is highly variable, and seasonal and edaphic conditions can mask crop response to shelter (Sudmeyer *et al*. 2002; Nuberg *et al*. 2002). Consequently, measurements or estimates of yield must be repeated over a number of years and at a number of sites for each crop species to determine a mean response to shelter. As part of the NWP, a model was developed (in part using data from this study) to simulate the growth of crops with varying degrees of shelter from the wind (Meinke *et al*. 2002). Carberry *et al*. (2002) used this model to estimate long-term crop yield at 17 locations around Australia using levels of wind protection similar to those provided by the shelters in this study. Accordingly, estimated long-term wheat yield was 6.9% higher in shelter at Esperance, 2.6% higher at Rutherglen and 13.1% higher at Warwick and mungbean yield was 6.9% higher at Warwick. Across all of the 17 sites, yield increases in shelter ranged between 0 and 29% and averaged 8.6% for all sites, years and crops. When Carberry *et al*. (2002) estimated crop yield at 5 H assuming that levels of wind protection varied during the growing season for one of the sites, yield increases were much smaller; ranging between 1.0 and 8.6%. Generally, shelter was least beneficial in those areas receiving in-season rainfall and most beneficial in areas receiving less in-season rainfall and greater probabilities of terminal water deficits (Carberry *et al*. 2002). The NWP also provides several field data sets that together show that microclimate changes and reduced wind speed in tree windbreak systems generally increase crop and pasture growth in southern Australia, but that these changes are not statistically significant (Sudmeyer *et al*. 2002; Bird *et al*. 2002*a*; Nuberg *et al*. 2002). Where measured changes in crop growth have been statistically and economically significant, they are usually associated with reduced physical damage such as that caused by sandblasting or excessive leaf movement (Jones and Sudmeyer 2002; Sudmeyer *et al*. 2002; Wright and Brooks 2002).

When the experimental results from this and other recent studies in tree windbreak systems (Bird *et al*. 2002*a*, 2002*b*; Nuberg *et al*. 2002; Sudmeyer *et al*. 2002) are seen in conjunction with simulated estimates of the economic returns from field windbreak systems (Carberry *et al*. 2002; Jones and Sudmeyer 2002) it is evident that windbreak systems in southern Australia should be designed with the principal aim of minimising physical wind damage rather than modifying microclimate.

Acknowledgments

Phil Haines, Philippa Noble, Phil Scott, Barbara George-Jaeggli and Jane Speijers are thanked for their scientific input. The cooperation of the landholders: University of Melbourne and Graeme and Barry Fisher of Browns Plains, Rutherglen, is greatly appreciated as is the assistance of the staff of Esperance Downs Research Station and staff at DPI Hermitage research station. All other members of the National Windbreak Program are thanked for their critical comment and input. This work was partially funded by the Rural Industries Research and Development Corporation.

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Received 1 September 1999, accepted 12 January 2002