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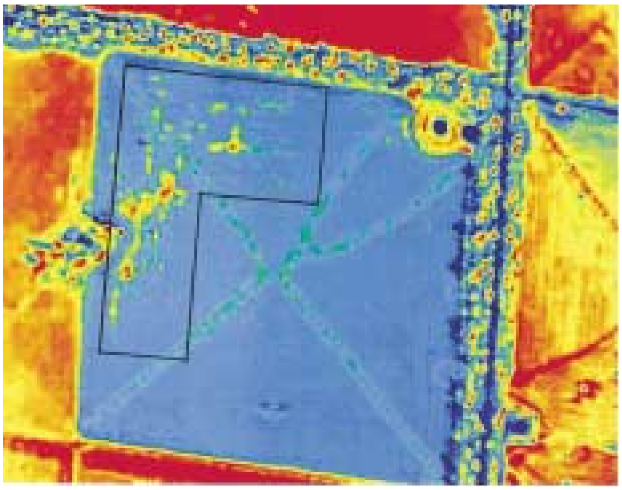

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Modelling crop growth and yield under the environmental changes induced by windbreaks. 2. Simulation of potential benefits at selected sites in Australia

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Abstract. Recent reports in Australia and elsewhere have attributed enhanced crop yields to the presence of tree windbreaks on farms. One hypothesis for this observation is that, by reducing wind speed, windbreaks influence crop water and energy balances resulting in lower evaporative demand and increased yield. This paper is the second in a series aimed at developing and using crop and micrometeorological modelling capabilities to explore this hypothesis. Specifically, the objectives of this paper are to assist the interpretation of recent field experimentation on windbreak impacts and to quantify the potential benefits and the likelihood of windbreak effects on crop production through an economic analysis of crop yields predicted for the historical climate record at selected sites in Australia.

The APSIM systems model was specified to simulate crop growth under the environmental changes induced by windbreaks and subsequently used to simulate the potential benefits on crop production at 2 actual windbreak sites and 17 hypothetical sites around Australia. With the actual windbreak sites, APSIM closely simulated measured crop growth and yield in open-field conditions. However, neither site demonstrated measurable windbreak impacts and APSIM simulations confirmed that such effects would have been either non-existent or masked by experimental variability in the years under study.

For each year of the long-term climate record at 17 sites, APSIM simulated yields of relevant crops for transects behind hypothetical windbreaks that provided protection against all wind. When wind protection from all directions is assumed, average simulated yield increases at 5 H (height of windbreak) ranged from 0.2% for maize at Atherton to 24.6% for wheat grown at Dalby, resulting in gross margin changes of –$14.79/ha.crop and $24.13/ha.crop, respectively, for a 10 m high windbreak and 100 ha paddock and assuming a 20% yield loss due to tree competition in the 1.0–3.5 H section. Averaged across all sites and crops, the simulations predicted a yield advantage of 8.6% at 5 H for protection from wind in any direction, resulting in an average gross margin loss of –$0.60/ha.crop. At the 8 sites with available data for wind direction, and assuming protection only from wind originating within a 90° arc perpendicular to a hypothetical windbreak which was optimally orientated at each site, average simulated yield increases at 5 H ranged from 1.0% for wheat at Orange to 8.6% for wheat grown at Geraldton. For a 10 m high windbreak, 100 ha paddock and an assumed 20% yield loss in the 1.0–3.5 H section, the average result across all sites and crops was a 4.7% yield advantage at 5 H and an average gross margin loss of –$2.49/ha.crop.

In conclusion, APSIM simulation and economic analyses indicated that yield benefits from microclimate changes can at least partly offset the opportunity costs of positioning tree windbreaks on farms.

Additional keywords: tree windbreak, simulation model, economic analysis.

Introduction

Convincing evidence exists for long-term benefits of retaining or planting trees on farms to rehabilitate land and protect the soil from erosion or salinity problems (Bird *et al.* 1992; Prinsley 1992). The incentive to plant trees would increase if there was widespread confirmation of reports of enhanced crop yields in the short term due to tree windbreaks (Bicknell 1991; Burke 1991; Sudmeyer *et al.* 2002*a*; A. J. Snell and S. J. Brooks pers. comm.). While reviews of the effects of windbreaks on farms have cited

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many reports from around the world of realised benefits, Grace (1988), Kort (1988) and Nuberg (1998) all contend that substantive evidence and quantitative understanding of the relationship between windbreaks and crop productivity is still required.

Of the several major hypotheses for why windbreaks elicit a crop response, prominent is the explanation that windbreaks beneficially alter the crop's microclimate and hence growth (Grace 1988; Cleugh 1998). However, while yield changes may be attributed to altered microclimates, in most field windbreak studies, the mechanisms for change remain equivocal. In order to attribute cause to and generalise the potential benefits of windbreaks, there is a need to be able to link changes in environment to the physiology of the crop and subsequent changes in crop yield.

Prinsley (1992) and Nuberg (1998) have strongly endorsed the need to use physically and biologically based simulation models as a means of better understanding and extrapolating the likely benefits from windbreaks. Easterling *et al*. (1997) used the EPIC model to explore the effect of windbreaks on maize productivity at 1 site in the USA. However, this effort concentrated on a hypothetical climate change scenario and admitted to limited validation of the microclimate assumptions used within the model.

In the first paper in this series, Meinke *et al*. (2002) described how the cropping systems model, APSIM (Agricultural Production Systems Simulator) (McCown *et al*. 1996), was specified to simulate crop growth under the environmental changes induced by windbreaks. APSIM simulation of potential evapotranspiration and crop growth under altered wind speed conditions was respectively tested against predictions from the SCAM micrometeorological model (Raupach *et al*. 1997) and limited crop data from artificial shelter experiments (Sudmeyer *et al*. 2002*b*).

The purpose of this second paper is to utilise APSIM to assist interpretation of recent field experimentation on windbreak impacts and to extend research results, beyond specific years and sites studied, to quantify likely economic benefits of tree windbreaks on farms. Most previous studies on economic benefits have suffered the drawback of needing to use set assumptions on likely yield effects (Nuberg 1998). This paper aims to quantify the potential benefits and the likelihood of windbreak effects on crop production through an economic analysis of crop yields predicted for the historical climate records at selected sites and for the expected range in microclimatic change induced by windbreaks around Australia.

Materials and methods

The 2 components of the subsequent analyses relate first to the simulation of field experimental data from Atherton (17.22°S, 145.57°E) and Esperance (33.83°S, 121.89°E) and second to the simulation of potential yield changes at selected sites around Australia

Table 1. Location of sites around Australia used in simulation analyses

Site	Lat. (°S)	Long. (°E)	Altitude (m)	Climate record Period	No. of years	Rainfall (mm)
			Queensland			
Atherton (Kairi)	17.22	145.57	714.5	1965–98	33	1262.5
Emerald (Speargrass)	23.53	148.16	280.0	1970–97	27	639.5
Dalby	27.18	151.26	343.8	1955–98	43	676.4
Hermitage	28.62	151.95	475.4	1965–98	33	784.0
			New South Wales			
Moree	29.50	149.90	212.1	1973–95	22	578.6
Gunnedah	31.03	150.27	307.0	1971–98	27	633.4
Orange	33.32	149.08	922.0	1976–98	22	946.5
Wagga Wagga	35.16	147.46	212.0	1972–98	26	585.2
			Victoria			
Rutherglen	36.11	146.51	167.6	1975–98	23	597.8
Horsham (Longerenong)	36.67	142.30	91.0	1983–98	15	430.4
			South Australia			
Roseworthy	34.53	138.69	114.0	1971–97	26	440.3
Minnipa	32.84	135.15	168.0	1965–85	20	326.5
			Western Australia			
Esperance	33.83	121.89	25.0	1969–98	29	612.7
Merredin	31.50	118.20	318.0	1972–85	13	313.2
Geraldton	28.80	114.70	32.7	1969–98	29	464.6
Kununurra	15.66	128.71	31.0	1970–97	27	784.4
			Northern Territory			
Katherine	14.48	132.25	103.0	1965–97	32	870.2

(Table 1; Fig. 1). Both sets of analyses required APSIM specified to simulate yields for altered wind speeds and climate, soil, crop and management data relevant to each simulation. The scenario analysis for selected sites additionally required economic data and an analysis that aggregated APSIM's point simulations to a paddock scale.

APSIM setup

APSIM (version 1.54), using crop modules for maize, mungbean and wheat, was used to predict the growth, development and yield of maize, mungbean and wheat crops grown at the sites nominated in Table 1. Meinke *et al*. (2002) described in detail how APSIM was specified to simulate crop performance behind windbreaks. Briefly, the following assumptions were employed:

(i) As APSIM crop modules have been developed and tested around Australia using a transpiration efficiency (TE) approach to determine daily transpiration demand (Carberry *et al*. 1996; Meinke *et al*. 1998), crop yields simulated at each site using this approach ($APSIM_{TE}$) were regarded as 'baseline yields' for the purposes of this analysis.

(ii) For APSIM to simulate the effects of wind on crop transpiration and soil evaporation, it was re-configured to enable potential daily evapotranspiration to be calculated using the Penman equation (Doorenbos and Pruit 1977) within the APSIM-EO module. Partitioning of potential evapotranspiration into a daily transpiration demand was achieved by multiplying potential evapotranspiration by daily values of green cover. Consequently, using this approach ($APSIM_{EO}$), yields are simulated as influenced by wind speed.

(iii) The APSIM-EO module (Penman, Doorenbos and Pruit model) requires input values of daily wind run (km/day). Two-thirds of the measured daily wind run was assumed to occur during the day.

(iv) Simulated transpiration demand, grain yield and total biomass using $APSIM_{EO}$ were compared to the 'baseline yields' from $APSIM_{TE}$ for open-field crops and for the historical climate record at each site. In most cases, $APSIM_{EO}$ predicted higher daily demands and consequently lower crop yields than $APSIM_{TE}$ (Meinke *et al*. 2002). Consequently, cumulative seasonal transpiration demand from $APSIM_{EO}$ was calibrated to equal that predicted by $APSIM_{TE}$ using a calibration factor (β) on daily transpiration demand. Each crop and site combination required this calibration to ensure $APSIM_{EO}$ predicted equivalent water use and crop yields to $APSIM_{TE}$. Values for β for each crop and site combination are presented in Table 2.

Figure 1. Location of experimental and simulation sites in the study region. Grey shading indicates the main cropping regions.

Simulation of experimental crops

As part of a national research program aimed at exploring the impacts of windbreaks in Australian dryland farming, crop and pasture performance behind established windbreaks were monitored over several seasons (Cleugh *et al*. 2002). Of 5 experimental sites, 2 sites, Atherton and Esperance, were suited to simulation of crop performance. The other sites either dealt with pasture species (not available within APSIM's suite of modules) or were affected by factors that made simulation difficult (significant soil variability, frequent waterlogging).

At Atherton, maize and potato crops grown behind 2 adjacent windbreaks, orientated in north–south and east–west directions, were monitored over 4 seasons (1993–97). Snell and Brooks (2002) have described the windbreak site and experimental procedures relevant to the potato crops. Similarly, maize was planted each year (in rotation with potato) and growth and yield were monitored at points along transects perpendicular to both windbreaks. In this paper, maize results from the 1994–95 season are simulated as this season experienced the greatest water deficit. It was the only season where an irrigated treatment was included in the experiment and results from the other seasons essentially confirmed the results from this 1 season. In the 1994–95 season, the maize cv. QK1472 was planted behind both windbreaks on 19 January 1995 at 33000 plants/ha with 115 kg N/ha applied as fertiliser. Biomass and yield harvests were conducted at silking (27 March) and physiological maturity (14 June) on 4 transects for dryland maize and on 2 transects for the small experimental irrigated area. Initial soil water and nitrate levels were measured before sowing and rainfall, maximum and minimum temperatures, solar radiation, wind run and wind direction were recorded daily by an automatic weather station on site. In 1994–95, the average height of trees within the windbreak was 7 m with a measured porosity of about 50% (Snell and Brooks 2002).

The Howick windbreak site, located 100 km east of Esperance, has been extensively described by Sudmeyer and Scott (2002*a*, 2002*b*). A measurement transect ran between 2 parallel north-east–south-west windbreaks 450 m apart. Of the 4 experimental seasons, only the 1996 barley crop was relevant to the analyses undertaken in this paper as APSIM modules for lupins and canola are still in a development phase. On 13 June 1996, the barley cultivar Stirling was planted at about 175 plants/ha with 60 kg N/ha applied as fertiliser. Rainfall, maximum and minimum temperatures, solar radiation, wind run and wind direction were recorded daily by an automatic weather station on site. In 1996, the average height of trees within the 2 windbreaks was 10.5 and 8.5 m with measured optical porosities of between 32 and 36% respectively (Sudmeyer and Scott 2002*a*).

APSIM was specified to simulate the experimental crops at both Atherton and Esperance — in the latter case, APSIM-IWheat was calibrated as a surrogate for a barley module. Crop growth and yields were simulated at nominated distances from the windbreak, equivalent to actual experimental sampling points, and for the open field at each of the 2 sites. Simulations used crop and soil parameter data appropriate to each site and all simulations were initiated with measured initial soil water and nitrate values. The irrigated maize treatment at Atherton was simulated by applying 25 mm of irrigation once plant available soil water content fell below 100 mm. As APSIM contained no module for potatoes, only the maize treatment was simulated at Atherton.

For each sampling point behind the windbreak, measured daily wind run was reduced using the relationship in Figure 2 between

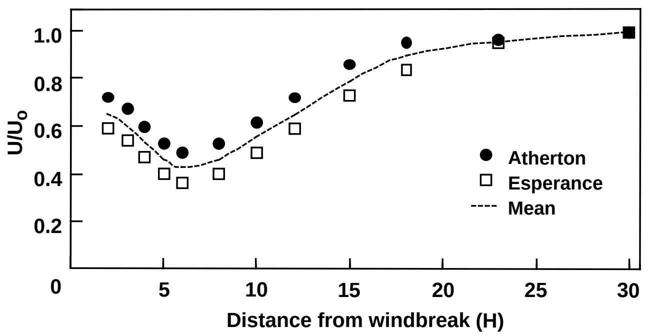

Figure 2. Relationships between the wind speed behind a windbreak (*U*) relative to open-field wind speed (*U*o) and distance from the windbreak (Cleugh 2002).

relative wind speed and distance from the windbreak calculated for each site (Cleugh and Hughes 2002). In these analyses, simulations assumed that all recorded wind originated from a single direction perpendicular to the windbreaks and that there was no competition from the tree windbreak with the adjacent crop. These assumptions provided a hypothetical upper limit to the yield benefits of the windbreaks and thus would indicate the likely accuracy that would have been required in experimental measurements.

Simulation of hypothetical scenarios

Table 1 lists the sites for which APSIM simulations were undertaken. Site selection was almost exclusively governed by the availability of long-term wind-run measurements and a desire to adequately cover the Australian cropping regions. The location of each site is shown in Figure 1. Measured daily wind run was collated for all recorded years for each site. Daily climate files were created for each site containing observed daily values for rainfall, maximum and minimum temperature, solar radiation, wind run and, where available, wind direction.

This scenario analysis deals with the single crop enterprises of dryland wheat, maize, or mungbean grown at those locations in Table 1 where such crops are commonly produced. Accordingly, the APSIM-Maize, Mungbean and IWheat modules (version 1.54) were used to predict crop performance for the duration of the climate record at each study site (Table 1) using the management regimes and soil parameters presented in Table 2. APSIM requires comprehensive descriptions of a soil to accurately simulate soil water and N balances. For this study, parameters for representative soil types for each location were collated and used. [The key parameter of maximum plant available water content (PAWC) for the soil used at each location is given in Table 2.]

For each simulation run, each year was treated independently; all parameters were re-initialised each year on the reset dates shown in Table 2. On these dates, soil mineral N status was reset to the nominated amount and soil water was re-initialised to a nominated percentage of

Table 2. Parameters used in open-field simulations at each site

Site and crop	β	Soil PAWC (mm)	Initial conditions: Reset date (day of year)	Initial SW (% full)	Initial N (kg/ha)	Sowing management: Sowing date (day of year)	N rate (kg/ha)	No. of plants (plants/m^2)
Atherton, maize	0.60	160	244	0	50	1	100	4
Emerald								
Mungbean	0.92	101	152	50	50	288	0	25
Wheat	1.00	—	335	50	50	135	100	100
Dalby								
Maize	0.86	239	152	50	50	288	100	7
Mungbean	0.92	—	152	50	50	288	0	25
Wheat	1.00	—	60	50	50	135	100	100
Hermitage								
Maize	0.86	218	152	50	50	288	100	7
Mungbean	0.92	—	152	50	50	288	0	25
Wheat	1.00	—	60	50	50	135	100	100
Moree								
Maize	0.86	159	152	50	50	288	0	5
Wheat	0.95	—	60	50	50	135	100	100
Gunnedah, wheat	0.95	171	60	50	50	135	100	100
Orange, wheat	0.65	125	1	0	50	135	100	100
Wagga Wagga, wheat	0.85	125	1	0	50	135	100	100
Rutherglen, wheat	0.85	172	1	0	50	135	100	180
Horsham, wheat	0.75	150	1	0	50	135	100	100
Roseworthy, wheat	0.70	175	1	0	50	135	70	180
Minnipa, wheat	0.65	70	1	0	50	135	70	100
Esperance, wheat	0.85	54	1	0	50	135	30	120
Merredin, wheat	0.70	146	1	0	50	135	30	120
Geraldton, wheat	0.85	69	1	0	50	135	30	120
Kununurra, mungbean	0.92	204	270	50	50	5	0	20
Katherine								
Maize	1.00	140	270	0	50	359	100	4
Mungbean	1.00	—	270	0	50	1	0	25

Table 3. Imposed windbreak direction and sector of protection at sites with available wind-direction data

Site	Windbreak orientation	Shelter sector
Emerald	000.0–180.0°	045.0–135.0°
Hermitage	045.0–225.0°	090.0–180.0°
Moree	135.0–315.0°	000.0–090.0°
Orange	135.0–315.0°	180.0–270.0°
Roseworthy	045.0–225.0°	270.0–360.0°
Minnipa	000.0–180.0°	225.0–315.0°
Esperance	202.5–022.5°	247.5–337.5°
Geraldton	292.5–112.5°	337.5–067.5°

PAWC (Table 2). For each site, we assumed that (i) the simulated crops followed a winter crop in the previous year that had fully depleted the available soil water, and (ii) the soil water profile would refill up to 50% full by day 152 before the subsequent summer crop. In the simulations, soil water was allowed to accumulate between the reset day and the date of planting as adequate weed control was assumed for this period. Planting was simulated on nominated fixed dates (i.e. planting occurs on the same day for every year of simulation). At the time of planting, information on crop genotype, sown population, sowing depth, and N fertiliser rates are required as model inputs (Table 2). In these simulations relatively high fertiliser N rates were applied to cereal crops to ensure that N was close to optimal and that simulated yield variation was principally due to differences in water availability and use.

Assessing the impact of a hypothetical windbreak on a crop was achieved by simulating yields at nominated distances from the windbreak, measured in units of equivalent windbreak tree heights (H). Yields were simulated at 2 H, 5 H, 10 H, 15 H and for open field (30 H). At each of these points behind the windbreak, measured daily wind run was reduced using the average relationship between relative wind speed and distance from the windbreak presented in Figure 2.

In a first case, simulations assumed that all recorded wind originated from a single direction perpendicular to the hypothetical windbreak (360° protection). In a second set of analyses, wind direction data for representative sites were used to determine the predominant wind direction during the cropping season (Table 3). The relationship in Figure 2 was then applied only to wind originating within a 90° arc that would be perpendicular to the hypothetical windbreak (Table 3).

Economic analyses

For each year of simulation, grain yields are adjusted to a set moisture percentage and gross margins ($/ha) are calculated using the prices and variable costs presented in Table 4.

To determine the aggregated impact of a windbreak on a crop, we assumed the simulated yields at a particular point behind the windbreak represented the average yield for that section of crop; i.e. simulated yields at 2 H, 5 H, 10 H, 15 H and 30 H represented the average yields for crop intervals 0–3.5 H, 3.5–7.5 H, 7.5–12.5 H, 12.5–20 H and the open field respectively. For a 1 m transect perpendicular to the windbreak, the economic impact of the windbreak can be calculated by summing the differences in gross margin (GM, $/m^2.windbreak height) between the GM achieved for each section and a GM calculated using open-field yield. The loss of land from planting a windbreak and resulting tree competition with the crop in the 0–3.5 H section was incorporated into the analyses by assuming 1 H of land area is completely lost to cropping and by discounting yields in the 1.0–3.5 H section by 20% each year. By assuming the height and length of windbreak (and a square paddock), a gross margin benefit or cost ($/ha) of the windbreak can be determined.

Table 4. Data used to calculate gross margin

	Maize	Mungbean	Wheat
Price ($/t)	120	560	160
Variable costs ($/ha)	114	200	180
Nitrogen fertiliser cost ($/kg)	0.82	0.82	0.82
Grain moisture (%)	12.0	12.0	12.0

Results

Simulation of experimental crops

For maize grown at Atherton in the 1994–95 season, yield simulations at the open field locations (30 H) for the 2 windbreak sites were close to measured values (Fig. 3). Simulations were almost identical for the 2 windbreak orientations given only small differences in starting soil water between sites. The simulation of the yield and biomass transects behind the windbreaks used either the assumption of no impact of altered wind speed on crop growth or assuming maximal wind reduction consistent with the relative wind speed relationship specified in Figure 2. With these assumptions, the simulated impact of the windbreak (the difference between simulations using either assumption) was largest at 6 H, with a 51% wind reduction resulting in a 14% increase in yield and 7% increase in total biomass compared to open field predictions (Fig. 3*a*). The simulated impact of the windbreak dissipated at points either closer to or further from the windbreak than 6 H and had largely disappeared by 18 H. Irrigating the maize crops negated the positive impact of wind-speed reductions on simulated maize yield and biomass (Fig. 3*b*).

The pattern in simulated yields at transect points behind the 2 windbreaks was not represented in the measured data (Fig. 3*a*). Differences in actual yields due to wind protection were either non-existent or too small to measure given the variability in observed data. This conclusion is supported by the simulation analysis — predicted growth changes were largely within the measurement error of the experiment, even though the simulations overestimated likely windbreak impacts (by assuming protection from all wind directions). No measured differences in yield despite small simulated effects of wind reduction were also found for the 1995–96 and 1996–97 seasons at Atherton (data not presented).

At Esperance, APSIM closely simulated the yield and biomass of barley grown at open field locations (20–24 H) in the 1996 season (Fig. 4). In fact, there was no significant difference in grain yield at transect points beyond the tree-competition zone (>3H) and, consequently, no enhanced yield effects could be attributed to the windbreaks (Sudmeyer and Scott 2002*b*). This result was supported by APSIM simulations, where altered wind speeds, based on the relationship in Figure 2, had no impact on simulated yields in the 3–10 H sheltered zone even if the windbreaks were assumed to provide protection from all directions.

Simulation of hypothetical scenarios

For each year of the climate record at the sites in Table 1, APSIM simulated yields of relevant crops for transects behind hypothetical windbreaks that provided protection against all wind. Using Hermitage as an example, Figure 5 shows simulated yield transects for the 3 crops in a year when there were large yield differences, a year when there was no impact and the average yield transect across all years.

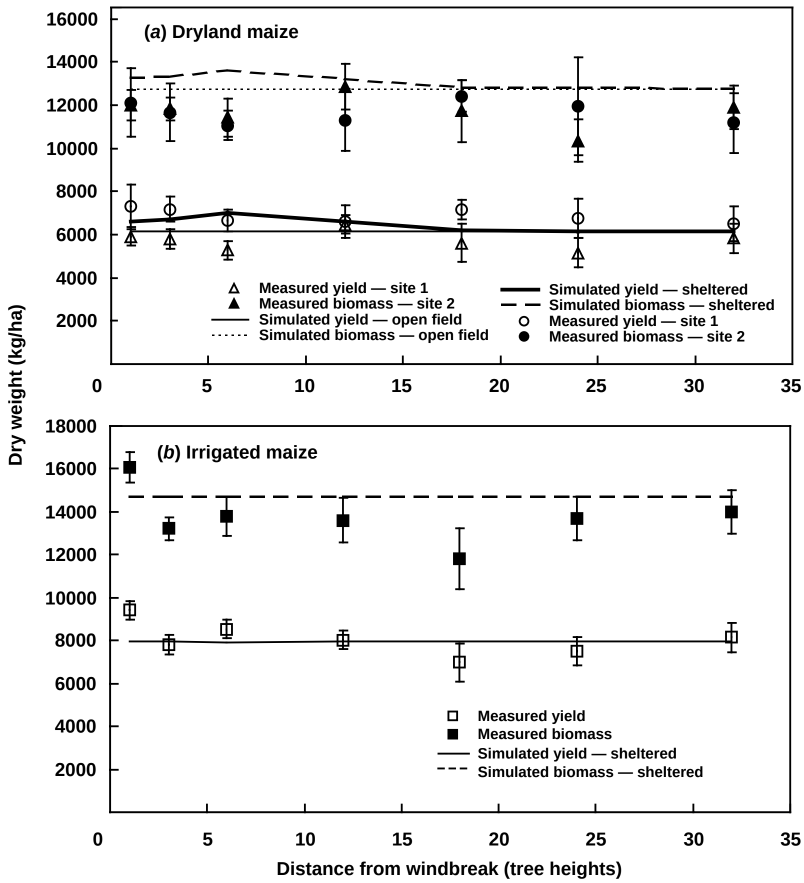

Figure 3. Simulated and observed grain and total biomass yields for (*a*) dryland and (*b*) irrigated maize crops grown at Atherton in the 1994–95 season.

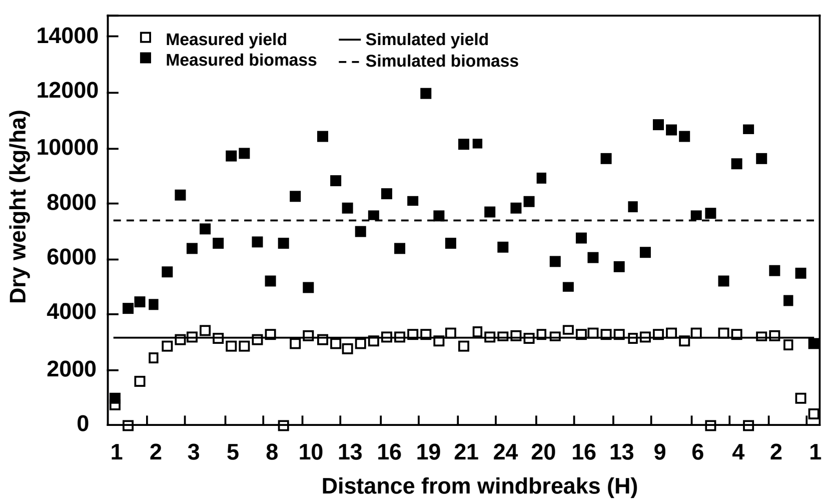

Figure 4. Simulated and observed grain and total biomass yields for barley grown near Esperance in the 1996 season.

In those years where simulated yields responded to reduced wind, the transects predicted by APSIM corresponded to the classical windbreak response as reported elsewhere.

Figures 6, 7 and 8 present for each year in the climate record of Hermitage, for maize, mungbean and wheat, respectively: (i) simulated yields for open field (30 H) and 5 H; (ii) the percentage change in simulated yields at 5 H compared with open-field yields; and (iii) the differential gross margins ($/ha) calculated for crops grown in 100 ha square paddocks behind a 10 m high windbreak compared to the equivalent area of fully exposed crop. These results demonstrate the variability in year-to-year responses and the differing impacts of reduced wind speed on the 3 crops simulated using the assumptions outlined earlier. Differences in simulated yield between 5 H and open-field yields averaged 7.1% for maize, 6.9% for mungbean and 13.1% for wheat due to a 55% reduction in daily wind speed

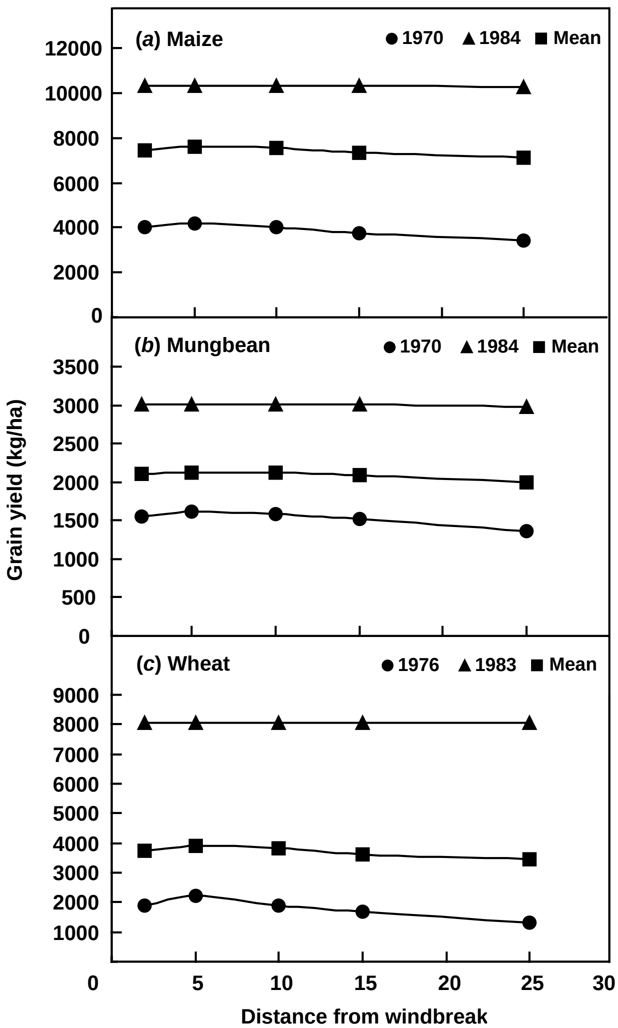

Figure 5. Simulated yield transects for the (*a*) maize, (*b*) mungbean and (*c*) wheat crops for particular years and for the average yield transect across all years.

(Table 5). The relative differences between crops were undoubtedly due to the initial conditions used in the simulation (Table 2). Mungbean showed the smallest response as soil water was initialised to 50% full — in many years, an adequate level for such a short-season crop. Conversely, soil water was initialised at lower limit for wheat that, in the northern grains region, would result in water deficits occurring in many years.

These analyses suggest that the introduction of windbreaks which (i) reduce the velocity of wind from all directions; (ii) occupy 1 H of land area that could have been alternatively cropped; and (iii) compete with crops for a distance of 3.5 H and reduce yields by 20% in this zone, will result in economic returns in some years and cost economic losses in other years. A typical (square) paddock at Hermitage (100 ha) with a 1000 m long windbreak of 10 m height on 1 side (having the above 3 characteristics) produced an average differential gross margin of $4.73/ha.year for wheat but a loss of –$3.07/ha.year for maize and –$3.01/ha.year for mungbean (Table 5). Clearly, such returns will change with windbreak height, paddock size and other factors such as prices, costs and management conditions. As an example, the gross margins for wheat at Hermitage increased for smaller paddocks and taller windbreaks (Fig. 9). Conversely, smaller paddocks and taller windbreaks reduced gross margins for maize and mungbean at this same site (data not shown).

In order to assess the effect of pruning roots of the windbreak trees, the discount on simulated yields due to competition in the 1.0–3.5 H zone was changed from 20% each year to no reduction. Thus, for a 100 ha paddock at Hermitage, average differential gross margins increased up to $6.82/ha.year, $1.04/ha.year and $2.71/ha.year for wheat, maize and mungbean, respectively (Table 5). Clearly, this simulated root pruning significantly increased the beneficial impact of the windbreak.

The preceding analyses assumed protection from winds of any direction. Figure 10 presents wind direction data averaged across all years at Hermitage. The dominant wind direction is from the south-east (135°) that suggests that a windbreak positioned along the 45–225° axis would provide maximal protection to both summer and winter crops (Table 3). Figure 11 shows simulation results for the impact of a windbreak on a wheat crop when only wind originating within a 90° arc perpendicular to such a windbreak (i.e. between 90 and 180°) is affected, using the relationship in Figure 2. The average difference in simulated yield between 5 H and an open-field wheat crop fell from 13.1% when all wind was discounted to 2.8% when account was taken for wind direction. For a 100 ha paddock at Hermitage with a 1000 m long windbreak of 10 m height situated along the 45–225° axis, the presence of the windbreak resulted in a loss of –$3.17/ha.year in average wheat gross margins. The frequency of beneficial effects also altered dramatically when wind direction was considered — only 13 of the 33 years (39%) produced positive gross margin gains compared to 26 years (79%) when protected from all wind directions (Figs 8 and 11). Accounting explicitly for wind direction dampened the yield advantage from the windbreak more for wheat than either of the 2 summer crops (Table 5). The proposed windbreak appeared less effectual in protecting from prevailing winds in winter than in summer at Hermitage.

Table 5 summarises the results of similar analyses for the 17 sites around Australia. When full wind protection is assumed, average yield increases at 5 H ranged from 0.2% for maize at Atherton to 29.1% for wheat grown at Merredin. The resulting gross margin changes ranged from –\$14.79/ha.year for maize at Atherton to \$24.13/ha.year for wheat at Dalby. Averaged across all sites and crops, the simulations predicted a yield advantage of 8.6% at 5 H for protection from all winds, and resultant gross margins of –\$0.60/ha.year and \$2.40/ha.year assuming either 20% or no tree competition. At the 8 sites with available data for wind direction, and assuming protection only from wind originating within a 90° arc perpendicular to a hypothetical

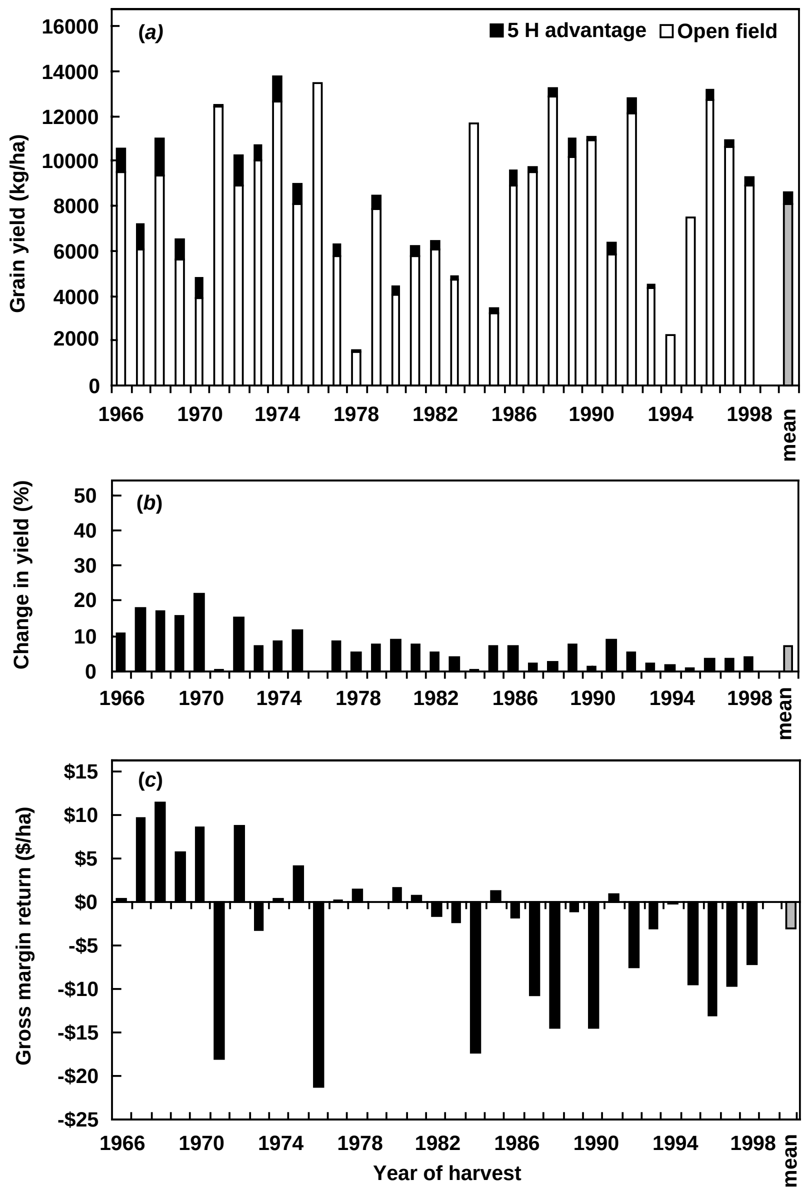

Figure 6. Maize crop at Hermitage: (*a*) simulated yields for open field (30 H) and 5 H, (*b*) the percentage change in simulated yields at 5 H compared with open-field yields, and (*c*) the differential gross margins (\$/ha) calculated for crops grown in 100 ha square paddocks behind a 10 m high windbreak compared to the equivalent area of fully exposed crop.

windbreak which was optimally orientated at each site, average simulated yield increases at 5 H ranged from 1.0% for wheat at Orange to 8.6% for wheat grown at Geraldton. For a 10 m high windbreak, 100 ha paddock and an assumed 20% yield loss in the 1.0–3.5 H section, the average result across all sites and crops was a 4.7% yield advantage at 5 H and an average gross margin loss of –$2.49/ha.crop.

Using a positive average gross margin differential as an arbitrary selection criterion, windbreaks appear unsuited to sites such as Atherton, Gunnedah, Orange, Wagga Wagga, Rutherglen, Horsham, Esperance, Kununurra and Katherine — essentially sites with high to medium in-season rainfall probabilities. The sites more suited to windbreaks, Dalby, Moree, Roseworthy and Minnipa, generally have lower in-season rainfall and higher probabilities of terminal water deficits. However, few of the sites with available data had positive average gross margin impacts when wind direction was taken into account (Table 5).

Discussion

Positive yield impacts of windbreaks were simulated in many years for the crops and sites in Australia considered in this study. Unfortunately, averaged over the available climate records, the simulated benefits resulting from microclimatic change induced by windbreaks are unlikely to offset the economic loss of land and tree–crop competition from

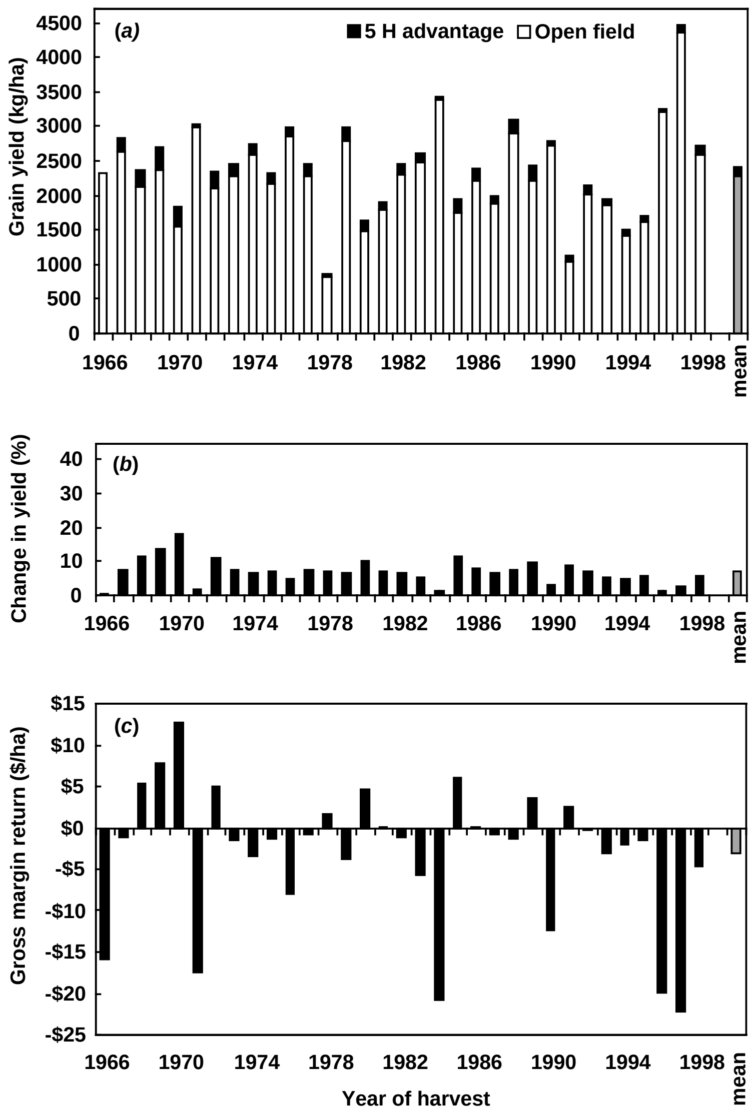

Figure 7. Mungbean crop at Hermitage: (*a*) simulated yields for open field (30 H) and 5 H, (*b*) the percentage change in simulated yields at 5 H compared with open-field yields, and (*c*) the differential gross margins ($/ha) calculated for crops grown in 100 ha square paddocks behind a 10 m high windbreak compared to the equivalent area of fully exposed crop.

establishing windbreaks on cropland at most locations in Australia. Thus, the simulation and economic analyses in this paper support the position that microclimate impacts alone are unlikely to justify the planting or maintenance of tree windbreaks on farms. Such justification needs to be the result of a combination of benefits in addition to an expected crop yield increase, for example the production of saleable wood, protection from damaging winds, assistance in lowering water tables, increasing biodiversity or simply valuing trees for their aesthetic appeal (Prinsley 1998).

While Table 5 quantifies likely yield and gross margin impacts of tree windbreaks, further justification of such analyses is certainly warranted. APSIM's capability to simulate the impacts of windbreaks on crop performance has been soundly based on established approaches to simulating crop yields and evapotranspiration demand in respond to wind (Meinke *et al*. 2002). However, validating this capacity has proven problematic. Meinke *et al.* (2002) successfully simulated observed biomass and yield responses to a limited number of artificially sheltered wheat and mungbean crops.

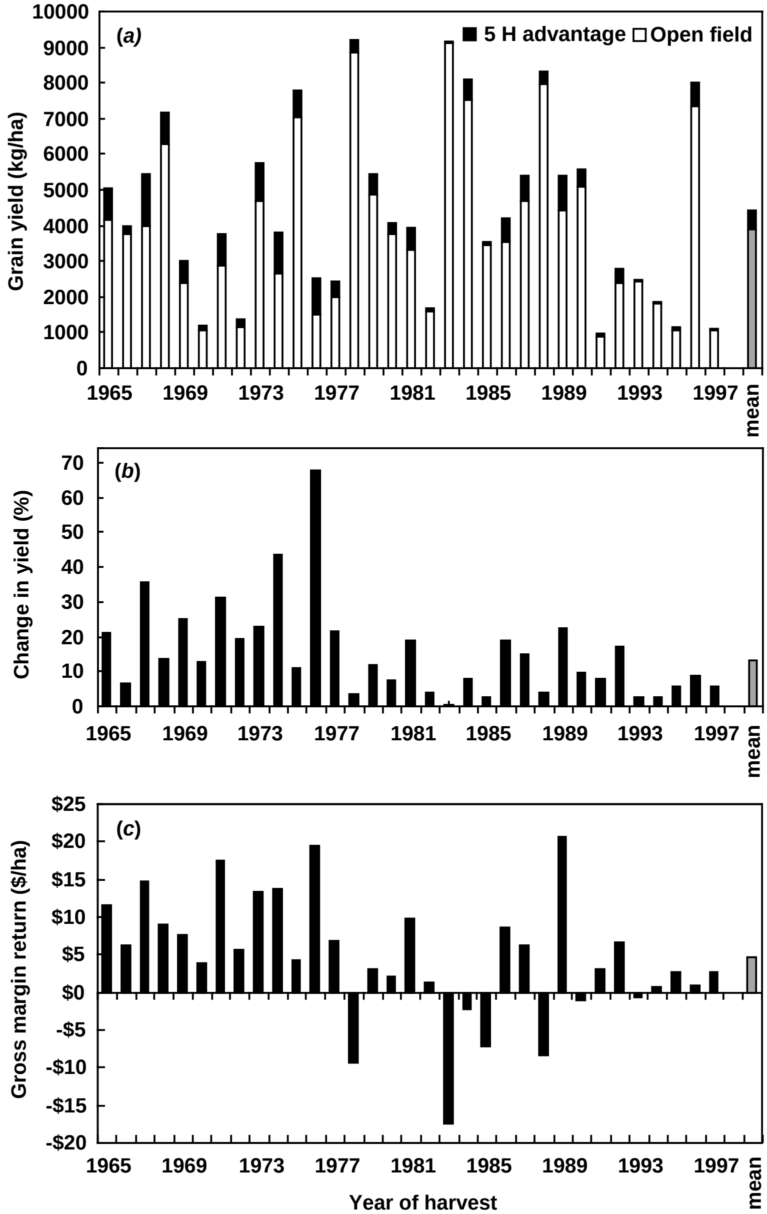

Figure 8. Wheat crop at Hermitage: (*a*) simulated yields for open field (30 H) and 5 H, (*b*) the percentage change in simulated yields at 5 H compared with open-field yields, and (*c*) the differential gross margins ($/ha) calculated for crops grown in 100 ha square paddocks behind a 10 m high windbreak compared to the equivalent area of fully exposed crop.

Table 5. Summary of simulation and economic analyses for each site and crop combination for windbreaks providing protection from all winds (360° protection) or partial protection (90° protection)

Mean change in gross margin (GM) was calculated using the assumptions of either 20% or no yield loss between 1.0 and 3.5 H

Site and crop	Full wind protection (360°)					Partial wind protection (90°)			
	Yield in open field (kg/ha)	Yield at 5 H (kg/ha)	Yield advantage (%)	GM change for 20% loss ($/ha)	GM change for no loss ($/ha)	Yield at 5 H (kg/ha)	Yield advantage (%)	GM change for 20% loss ($/ha)	GM change for no loss ($/ha)
Atherton, maize	8717	8726	0.2	–14.79	–3.38	—	—	—	—
Emerald									
Mungbean	1026	1044	1.8	–5.12	–2.81	—	—	—	—
Wheat	1520	1620	6.6	2.55	2.70	1548	1.8	0.91	0.84
Dalby									
Maize	4670	5313	14.9	3.90	6.37	—	—	—	—
Mungbean	1627	1787	10.0	–0.40	4.09	—	—	—	—
Wheat	3657	4558	24.6	24.13	27.04	—	—	—	—
Hermitage									
Maize	7124	7579	7.1	–3.07	1.04	7329	3.0	–7.88	–3.90
Mungbean	2000	2127	6.9	–3.01	2.71	2087	4.7	–6.51	–0.89
Wheat	3438	3888	13.1	4.73	6.82	3533	2.8	–3.17	–1.29
Moree									
Maize	2659	2870	7.9	1.42	2.36	2831	6.4	0.65	1.57
Wheat	2960	3234	9.3	2.34	3.87	3159	6.7	0.06	1.54
Gunnedah, wheat	3699	3845	4.8	–5.89	–0.57	—	—	—	—
Orange, wheat	4273	4359	2.0	–5.21	–2.58	4315	1.0	–6.48	–3.88
Wagga Wagga, wheat	4037	4312	6.8	–0.95	1.56	—	—	—	—
Rutherglen, wheat	4188	4296	2.6	–5.04	–2.48	—	—	—	—
Horsham, wheat	3141	3314	5.5	–0.14	1.73	—	—	—	—
Roseworthy, wheat	4307	4856	12.8	5.46	8.57	4614	7.2	–1.52	1.38
Minnipa, wheat	2721	3274	20.3	7.78	9.36	2875	5.7	–0.70	0.67
Esperance, wheat	2961	3135	6.9	–1.44	0.39	3016	3.3	–3.67	–1.97
Merredin, wheat	1255	1620	29.1	6.70	6.41	—	—	—	—
Geraldton, wheat	2775	3057	10.2	1.95	3.63	3014	8.6	0.92	2.57
Kununurra, mungbean	1858	1874	1.0	–11.41	–7.18	—	—	—	—
Katherine									
Maize	3934	3974	1.0	–4.34	–2.61	—	—	—	—
Mungbean	1900	1907	0.3	–14.55	–9.49	—	—	—	—

Yet no validation data were available from field sites that demonstrated significant yield impacts in the lee of a tree windbreak.

At 2 measured windbreak sites, Atherton and Esperance, APSIM closely simulated crop growth and yield in open-field conditions (Figs 3 and 4). One intention of this study was to utilise APSIM to assist interpretation of recent field experimentation on windbreak impacts (Cleugh *et al*. 2002). For the 1996 barley crop at Esperance, APSIM simulations indicated no impact of altered wind speed on crop transpiration, growth and yield — in this season there was sufficient soil water supply to meet evapotranspiration demand. For maize crops grown at Atherton over several years, APSIM simulated small yield responses to altered wind speed (assuming total protection), yet they were largely of the same magnitude as the sampling variability in the experiment (Fig. 3). The probability of achieving measurable differences in crop performance due to tree windbreaks requires situations of high evaporative demand driven by

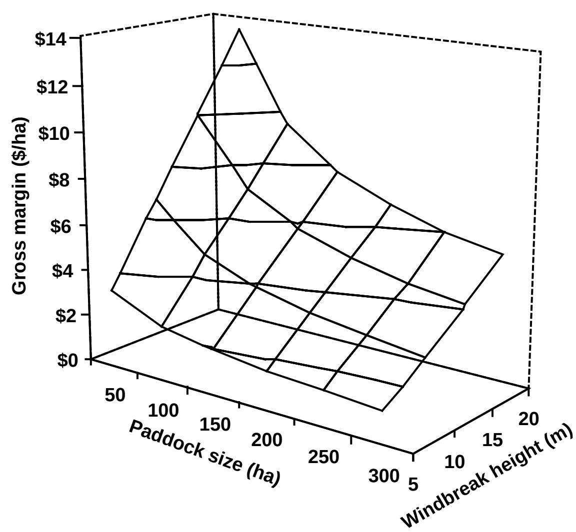

Figure 9. The change in gross margin benefit with windbreak height and paddock size for wheat at Hermitage.

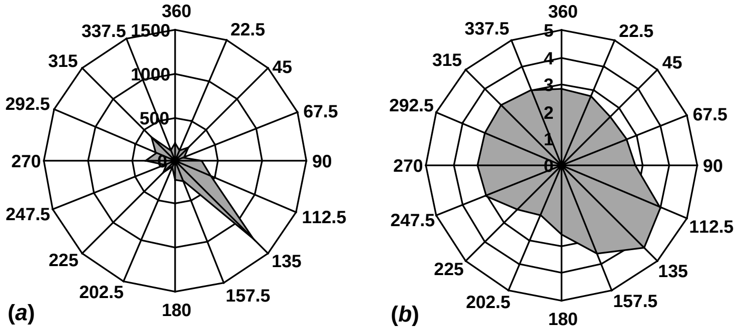

Figure 10. Frequency of (*a*) daily wind direction and (*b*) average wind speed (m/s) across the 33 years (15 October–16 March) of climate data for Hermitage.

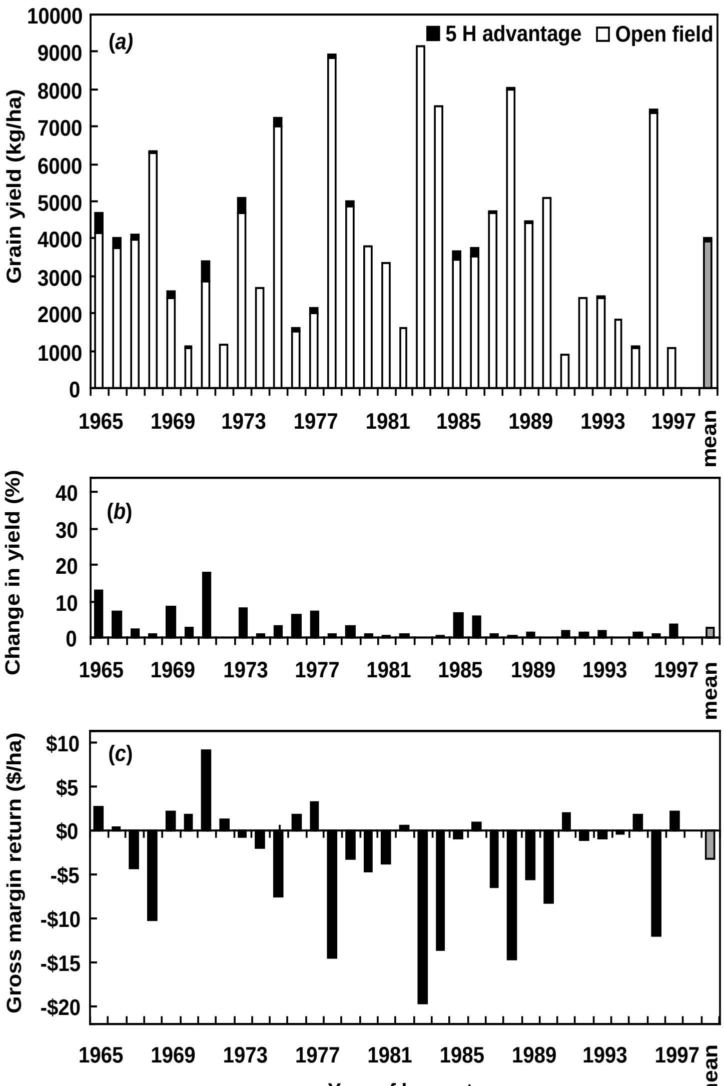

Figure 11. Wheat grown behind a windbreak positioned along the 45–225° axis at Hermitage: (*a*) simulated yields for open field (30 H) and 5 H, (*b*) the percentage change in simulated yields at 5 H compared with open-field yields, and (*c*) the differential gross margins ($/ha) calculated for crops grown in 100 ha square paddocks behind a 10 m high windbreak compared to the equivalent area of fully exposed crop.

aerodynamic influences corresponding with deficits in soil water supply (Easterling *et al*. 1997). The long-term simulation analyses at Esperance and Atherton (Table 5) suggest that such conditions are infrequent at these sites for crops grown under typical management conditions — both sites are mostly well watered for crop production.

In fact, of the 4 experimental windbreak sites (Atherton, Esperance, Roseworthy and Rutherglen; Fig. 1), which were established as part of a national windbreak program (Cleugh *et al*. 2002), long-term simulation and economic analyses (Table 5) indicate that only at Roseworthy would significant impacts of windbreaks be likely. Unfortunately, other factors such as soil variability, have made it difficult to interpret the data from Roseworthy (Nuberg *et al*. 2002). A significant learning from this national program therefore has been the difficulty in measuring yield impacts of windbreaks due to microclimate influences using field experimental techniques with large inherent measurement variability; a situation also observed by Nuberg (1998) in his review of the windbreak literature. Multi-site and crop surveys (Sudmeyer *et al*. 2002*a*), artificial shelters (Sudmeyer *et al*. 2002*b*) and simulation analyses, such as conducted in this paper, provide alternative means of quantifying the impacts of windbreaks on crop performance. Certainly, the analyses summarised in Table 5 provide an indication of which sites and crops could be targeted in future windbreak experiments; Dalby and Minnipa (Fig. 1) are obvious choices.

Under the assumptions used in the simple economic analyses summarised in Table 5, the incorporation of windbreaks on croplands is unlikely to result in a long-term financial benefit at many of the selected sites. Modifying some of these assumptions can alter this conclusion. Reducing the area planted to trees and root pruning both significantly reduce the downside cost of windbreaks. Likewise, planting crops using management options that increase risk of water deficits (e.g. double cropping, delayed planting, high populations and fertiliser rates) will enhance the value of windbreaks — although it would be difficult to justify establishing windbreaks based on atypical cropping scenarios. In contrast, the economic analyses proved to be largely insensitive to price : cost ratios, mainly because these factors influenced both the upside (higher yields) and downside (loss in cropland, tree competition) attributes of tree windbreaks.

The economic analysis is deficient in several important areas that may influence its conclusions. The analysis ignored the establishment costs of the windbreak, the costs and returns from production of saleable wood, the aggregated benefits of windbreaks over a sequence of years (as opposed to a response on average), the influence of infrequent wind-damaging events (sandblasting, erosion), and the possible enhanced value of windbreaks as protection against downside risk (i.e. a dollar benefit in a poor year is worth more to a risk-averse farmer than the equivalent benefit in a good year). Brandle *et al*. (1992) employed a net present value (NPV) analysis to explore the long-term economics of windbreak systems in the USA, but this analysis was limited by using assumed yield scenarios. Jones and Sudmeyer (2002) used a NPV analysis and surveyed yield responses to evaluate windbreaks in Western Australia. They concluded that windbreaks improved farm profitability only when risk of wind erosion was significant.

In conclusion, APSIM has proven a cost-effective and appropriate tool to assessing the likely benefits of changed microclimate due to tree windbreaks on croplands at selected sites in Australia. Notwithstanding the assumptions taken in using APSIM for this reason, subsequent simulation and economic analyses indicated that yield benefits would be less than required under most cropping scenarios to fully compensate for the opportunity costs of positioning tree windbreaks on farms.

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