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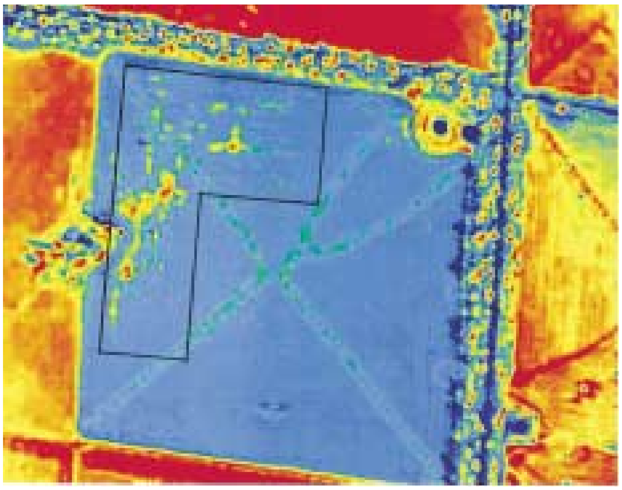

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Effect of windbreaks on potato production for the Atherton Tablelands of North Queensland

A. J. Wright[A] *and S. J. Brooks*

Queensland Forest Research Institute, PO Box 629, Atherton, Qld 4883, Australia.
[A]Author for correspondence; e-mail: Amanda.Wright@nrm.qld.gov.au

Abstract. The effect of windbreaks on the growth and yield of potatoes was measured over a 4-year period. Growth measures included the amount and severity of wind damage to leaves, plant height and number of leaves. Plots were located at various distances from the windbreak in both sheltered and unsheltered positions. The results of this project, while variable both within and between seasons, suggest that windbreaks increase the yield of potatoes between 4.8 and 9.3% for the sheltered portion of the paddock in seasons with higher than average wind speeds. A significant increase in yield has been observed between 3 H and 18 H (where H is the height of the windbreak) in seasons where wind speed was above average, although this result varied within seasons. Increased yield was attributed to a reduction in wind damage to leaves on plants growing in sheltered positions, where it was recorded.

Introduction

The importance of wind shelter in agricultural systems has long been recognised (Cardwell 1936; Bates 1944; Ferber 1958; Grace 1988; Norton 1988); however, our knowledge of how crops respond to windbreaks in Australia is inconclusive (Brandle *et al*. 1992). Wind is known to cause physical damage to crops by: the abrasion of leaves and fruits (Kort 1988; Sun and Dickinson 1997) and lodging of mature crops (Marshall 1967). Wind also causes changes in plant physiological function as a result of both physical damage and microclimatic variables (McNaughton 1988; Grace 1989; Sun and Dickinson 1997; Cleugh 1998). In areas where vegetation is sparse, wind also causes severe soil erosion (Maki *et al*. 1991; Nanney *et al*. 1993). The awareness of the potential wind damage has led to the planting of trees as windbreaks in agricultural management systems.

The effect of wind shelter on final crop yield may vary greatly between crops, situations and seasons (Grace 1988). Many studies document yield increases in crops (Baldwin 1988; Dry *et al*. 1989; Eckstein *et al*. 1996; Sun and Dickinson 1997) and benefits to livestock production (Reid and Bird 1990). Others (Zhang and Brandle 1996, 1997; Crawford 1998; Nuberg and Mylius 1998) show no effects of windbreaks on crop yields. For example, Zhang and Brandle (1996, 1997) compared modelled and measured grain yields for maize under sheltered and unsheltered conditions. They found no significant increase in total leaf area, vertical distribution of leaf area, biomass or grain mass behind windbreaks, indicating that microclimatic changes induced by windbreaks were not physiologically significant. Hodges and Brandle (1996) stated that windbreaks increase soil and air temperatures, improve plant water relations and irrigation efficiency, reduce pest and disease problems and can extend the growing season in sheltered areas, resulting in faster crop development, earlier crop maturity and market advantage.

Wind is known to have direct mechanical effects on crops capable of altering growth rates and leaf morphology, uprooting plants, causing physical leaf damage, stripping, abrasion, sandblasting, and combined abrasion and tearing (Cleugh *et al*. 1998). Many studies have recorded a reduction in abrasive damage to plants provided with wind protection (Grace 1974; Thompson 1974; MacKerron 1976; Pitcairn and Grace 1984; Sun and Dickinson 1994, 1997). Thompson (1974) observed damage to the leaves of *Festuca arundinacea* in a wind tunnel and reported microscopic damage to the epidermis including the rupture of epidermal cells, cracking of the cuticle, and smoothing and redistribution of the wax deposits that cover the surface. Grace (1974), in an analogous experiment, concluded that leaves where epidermal damage had occurred might have lost their capacity for controlling water loss. Campbell (1998) reported that reducing wind speed using a windbreak significantly increased water use and potential yield in grapevines in Western Australia.

The Atherton Tablelands are a major agroecological zone in Australia and are exposed to constant winds, which generally originate from the south-east. This study was part of a nationally coordinated research program on windbreaks, and was specifically designed to analyse the effects of windbreaks on potato production on the Atherton Tablelands and examine how the effects (if any) occur, either by reducing the amount of physical crop damage or by influencing the canopy microclimate.

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Materials and methods

Site description

The site used for windbreak studies was situated roughly 10 km north of Atherton (17°15′S; 145°29′E; altitude 710 m). The site had no apparent slope and a deep, red krasnozem soil. Average annual rainfall is 1400 mm, the bulk of which generally falls between December and May. The average daily temperatures range from 19.6 to 30.6°C during summer and from 13.0 to 24.8°C during winter.

Maize (*Zea mays* L.), potato (*Solanum tuberosum* L.) and peanut (*Arachis hypogaea* L.) have been grown on a rotation system at the site for the past 50 years, although sugarcane (*Saccharum officinarum* L.) is now grown in selected paddocks. Maize and peanut are grown during the warmer, wetter months (November–May) and are not irrigated; potato is grown during the cooler, drier months (May–October) and is irrigated.

Windbreaks planted in 1992 comprise 2, 3 or 4 rows and consist of trees with a variety of growth habits, including small (up to 6 m), medium (up to 30 m) and tall (up to 40 m). Small trees included *Melaleuca armillaris* (Sol. ex Gaertner) Smith, *M. linariifolia* Smith, *Callistemon salignus* (Smith) DC. and *C. viminalis* (Sol. ex Gaertner) G. Don ex Loudon. Medium trees included *Eucalyptus tessellaris* F. Muell., *E. torelliana* F. Muell. and *Grevillea robusta* Cunn. Ex R. Br. The tall species included *E. microcorys* F. Muell. and *Pinus caribaea* var. *hondurensis* Morelet. Windbreaks were positioned in either a north–south or east–west direction to give protection from the prevailing south-easterly winds (Fig. 1). North–south windbreaks were on the eastern side of the property only; there were no windbreaks along the western boundary. The optical porosity of these windbreaks was between 48 and 54%, depending on windbreak species (H. Cleugh pers. comm.).

Plot establishment

Experiments were carried out in a number of paddocks over the 4 years of the study (Table 1). Plots were located along 4 or 5 transects which were positioned perpendicular to either north–south or east–west orientated windbreaks. In each year, 2 replicate sets of transects were measured. Plot distances were calculated in multiples of the windbreak height (H), adjacent to each replicate. For example, a plot located at 3 H adjacent to a 9 m tall windbreak would be 27 m from the windbreak (Table 1).

Each plot consisted of 2 rows, 4 m wide, with an intensive measurement (net) plot of 2 rows by 1 m within. Plots were thinned to give a uniform plant number of 55 555 plants/ha.

Crop growth

The plants in the net plot were measured fortnightly. Parameters measured in each net plot included number of plants, foliage cover and plant height at the 4 corners. In each net plot, 3 plants were randomly selected, permanently marked, and measured for height, leaf number, number of dead leaves, and the length and width of the 3 youngest, fully expanded leaves on each plant. In all years except 1994, the number of insect damaged leaves and relative degree of wind damage on each leaf were also measured. In all years except 1994, wind-damaged leaves on the 3 selected plants were rated as follows: (i) no damage, leaf intact; (ii) minor damage, a few small lesions; margin intact; (iii) moderate damage, lesions; margin with small tears; and (iv) severe damage, many large lesions and or holes in leaf blade; margin with long tears. The proportion of each damage category was calculated as a percentage of total leaf number.

The final harvest was conducted at physiological maturity after plant tops were dry and removed from the paddocks (Table 1 for dates).

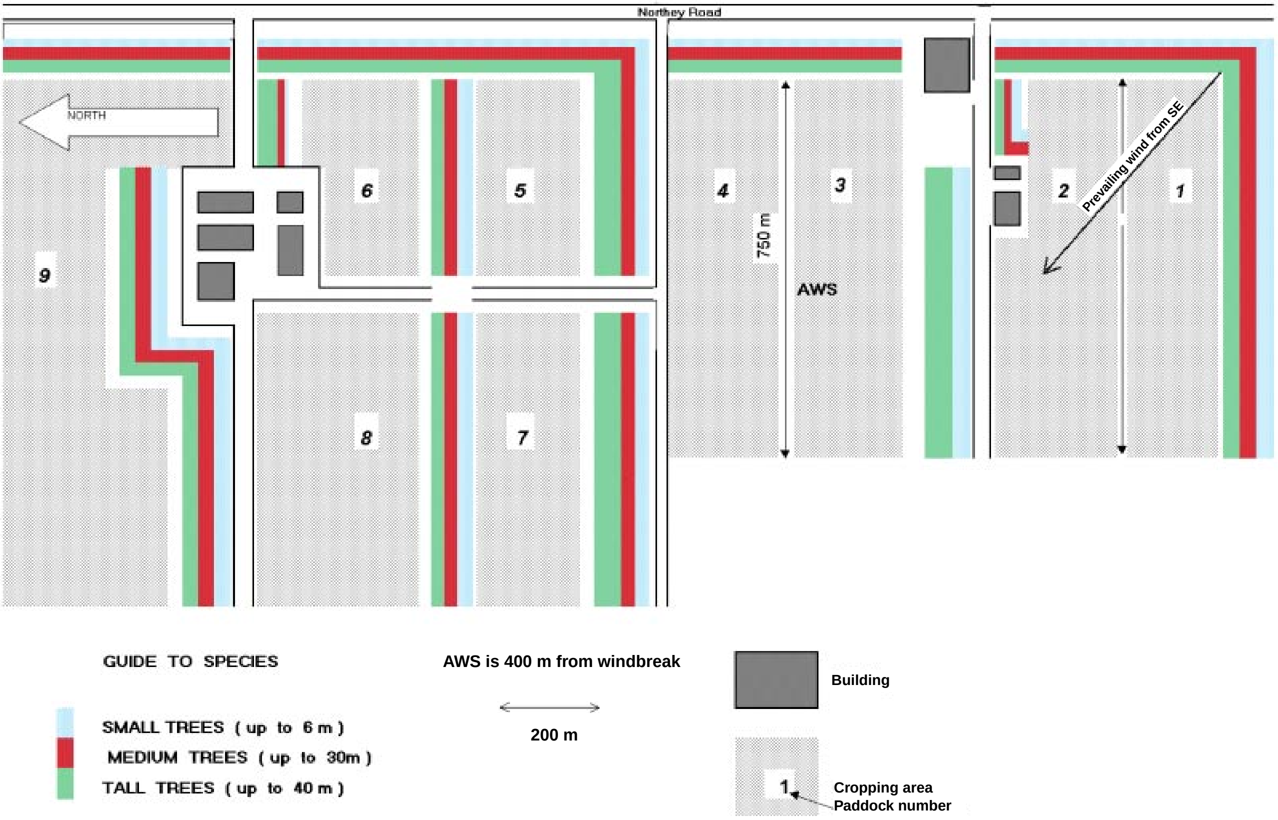

Figure 1. Site layout (NTS) showing paddock number and windbreak arrangement.

Table 1. Summary of measurements and agronomy of *Solanum tuberosum* between 1994 and 1997

Year	Replicate	1994	1995	1996	1997
Paddock number and transect direction	R1	4, west	7, north	2, west	4, west
	R2	4, north	3, west	1, west	3, west
Windbreak height (m)	R1	6	6.2	7.5	9
	R2	6	6	7.5	9
Plot locations (H)	R1	1, 3, 6, 12, 18, 24 and 30	1, 3, 6, 12, 18, 24 and 28	1, 3, 6, 12, 18, 24, and 40	1, 3, 6, 12, 18, 24 and 32
	R2	1, 3, 6, 12, 18 and 24	1, 3, 6, 12, 18, 24 and 32	1, 3, 6, 12, 18, 24, and 40	1, 3, 6, 12, 18, 24 and 32
Potato cultivar	R1-3	Atlantic	Atlantic	Atlantic	Atlantic
Planting date	R1	24 June 1994	29 May 1995	29 May 1996	8 April 1997
	R2	25 June 1994	11 June 1995	18 June 1996	22 April 1997
Fertiliser applied at planting		Q5 (NPK) band application	CK5 band application	CK5 band application	CK5 band application
Fertiliser rate (kg/ha)		2000	1750	1750	1750
Other fertiliser applied with irrigation water		Urea (46% N)	Urea (46% N)	Urea (46% N)	Urea (46% N)
Fertiliser rate (kg/ha)		150	150	150	150
Fertiliser timing		4 weeks after sowing	4 weeks after sowing	4 weeks after sowing	4 weeks after sowing
Target population (plants/ha)		55555	55555	55555	55555
Germination		R1: 9.vii.94; R2: 11.vii.94	R1: 20.vi.95; R2: 13.vi.95	R1: 15–17.vi.96; R2: 2.vii.96	R1: 26.v.97; R2: 8.vi.97
Interim harvest		R1: 22.viii.94; R2: 24.viii.94	R1: 14.viii.95; R2: 31.vii.95		R1: 30.vi.97; R2: 4.viii.97
Final harvest		R1 and 2: 7.x.94	R1: 19.ix.95; R2: 6.ix.95	R1: 12.ix.96; R2: 1.x.96	R1: 14.viii.97; R2: 11.ix.97

The entire plot (2 rows by 4 m) was harvested for all potato tubers. The total potato tuber yield was sorted into A-grade (marketable) and reject (unsaleable and small) potatoes.

Microclimate measurements

A number of microclimatic parameters, including air and soil temperature, solar radiation, relative humidity, rainfall, and wind direction and speed were recorded and averaged every 15 min throughout the duration of experiments using a 'Datataker' Automatic Weather Station (AWS). The weather station was situated in an exposed (not sheltered) area on the site; 400 m from the nearest windbreak to the east and 210 m from the nearest windbreak to the south. Soil temperature was measured at a depth of 5 cm below the soil surface and all other parameters were measured at a height of 2 m above the ground.

Soil measurements

Along each transect in each replicate in 1994, soil samples were taken at depths of 0–15, 15–30, 30–45, 45–60 and 60–90 cm beside each plot 3 days after potato planting. The soil sampled at the same H and at the same depth was bulked and subsamples taken for final chemical analysis for available N, P, and K and organic carbon. The results were published by Sun and Dickinson (in 1997), and showed that N, P, K and organic carbon varied little between the 7 distances from the windbreak. These measurements were not repeated in subsequent years.

Data analysis

Individual replicate data were used in subsequent analyses in order to fully utilise data from separate transects. Multiple samples were taken at each sampling point along each transect. Analysis of variance and Fisher's least significant difference tests were performed on harvest data using the GENSTAT package. ANOVA tests established whether treatment effects were significant by comparing sample means with the variation within samples (Scheffé 1959; Ott 1988). Where treatment effects were found to be significant from ANOVA tests, Fisher's least significant difference (l.s.d.) was calculated and sample means were divided into groups accordingly (Ott 1988). Sigma-Plot (Jandel Scientific) was used to graph results and for regression analysis where appropriate. Sigma-Plot uses the Marquardt-Levenberg algorithm to find the coefficients of the independent variable that give the 'best fit' between the equation and the data (Marquardt 1963; Press *et al.* 1986). Modelled data iterated by Sigma-Plot were used to calculate percentage increases to yields where appropriate.

Results

Microclimate

The microclimatic parameters were averaged over the potato growing season for each year between 1994 and 1997 (Table 2). The prevailing wind at the site blew from the

Table 2. Microclimatic variables measured by the automatic weather station for each growing season (April–September)

Means followed by the same letter are not significantly different at $P = 0.05$

Year	Total rainfall[A] (mm)	Average air temperature (°C)	Average soil temperature (°C)	Average relative humidity (%)	Average wind speed (m/s)	Average maximum wind gust (m/s)	Average wind direction (°)
1994	—	16.8a	21.5c	75.5a	4.01c	9.41	—
1995	359	18.0b	21.0bc	83.3b	3.25b	8.52	—
1996	266	18.2b	20.4b	83.2b	2.90a	8.37	—
1997	138	16.8a	15.1a	88.1c	3.90c	9.36	137

[A] The potato crop was irrigated on a regular basis and the rainfall values do not include this additional source of water.

south-east (90% of total wind); 68% from the east to south-east and 22% from the south to south-east. This south-easterly wind pattern is typical for the Atherton Tablelands (Bureau of Meteorology 1999). The average (± s.d.) annual wind speed for the period of this study was about 3.68 (± 0.25) m/s and the average maximum wind gust was 9.18 (± 1.41) m/s. The mean daily wind speed was significantly lower in 1996 than for all other growing seasons. Relative humidity was significantly lower in 1994 and significantly higher in 1997 than in 1995 or 1996. Average daily air temperature was significantly lower in 1994 and 1997 than other years. The average soil temperature also varied significantly between years with 1997 being significantly lower and 1994 significantly higher. Further analysis of the microclimate measured by the Automatic Weather Station at the site is summarised in Cleugh (2002).

Yield

The yield of A-grade potato tubers generally increased for plants located between 3 and 6 H and up to 18 H compared to yields at >20 H (Fig. 2). In all years except 1996, a relatively clear trend towards increased yield of A-grade potatoes as a result of wind protection can be seen. The increased yield was significant in 1994 (replicate 2) and 1997 (replicate 1). In 1996 (replicate 2) yield was significantly decreased at 1 H compared with all other distances. Note that the significant increase in yield in 1996 was only noted between 1 H and all other positions and was due to windbreak competition rather than a windbreak effect. The average potato tuber yield was highest in 1996 and lowest in 1995 than for other years. The effects of crop competition (lower yields at 1–3 H) with the windbreak can be observed in all replicates except 1996, replicate 2.

Where differences in potato yield were significant, the Sigma-Plot graphing package (Jandel Scientific) was used for regression analysis and calculation of the net percentage change in potato yield compared with yield at >20 H. A number of regression models were tried (including the critical exponential model used by Sun and Dickinson 1997), but a 4-parameter, log-normal function was found to provide the best fit;

$$y = y_0 + a \exp\{-0.5\ [\ln (x/x_0)/b]^2\}$$

where y_0 is the predicted minimum yield, x_0 is the distance from the windbreak where maximum yield occurs, and a and

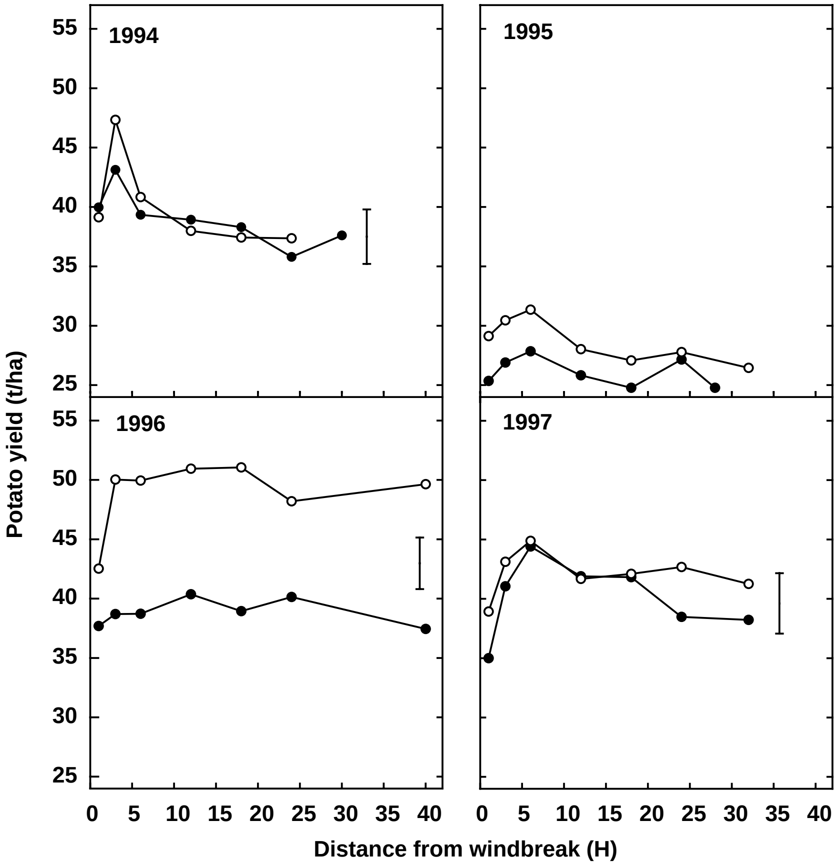

Figure 2. Potato yields (● replicate 1, ○ replicate 2) at different distances from windbreaks for the 4 years of this study. Vertical bars indicate the l.s.d. at $P = 0.05$.

b are coefficients of the equation. (Sigma-Plot automatically estimates the initial parameters for y_0 and x_0 from the data.)

The following regression best described changes in potato yield in 1994 (replicate 2):

$$y = 37.50 + 9.9550 \times \exp\{-0.5 \times [\ln (x/2.7438)/0.5324]^2\};\ (P<0.0002,\ R^2 = 0.63).$$

The following regression best described changes in potato yield in 1997 (replicate 1):

$$y = 31.8913 + 12.0072 \times \exp\{-0.5 \times [\ln (x/7.2058)/1.2240]^2\};\ (P<0.0019,\ R^2 = 0.40).$$

Figure 3 shows the fitted curves.

There was an overall increase in potato tuber yield of 4.81% within 20 H of the windbreak in 1994 (significant increase in yield at 3 H). Average modelled yield >20 H was 37.5 t/ha and average yield <20 H was 39.3 t/ha. There was an overall increase in potato tuber yield of 9.37% within 20 H of the windbreak in 1997 (significant increases were measured between 3 H and 18 H). Average modelled yield >20 H was 37.5 t/ha and average yield <20 H was 41.0 t/ha.

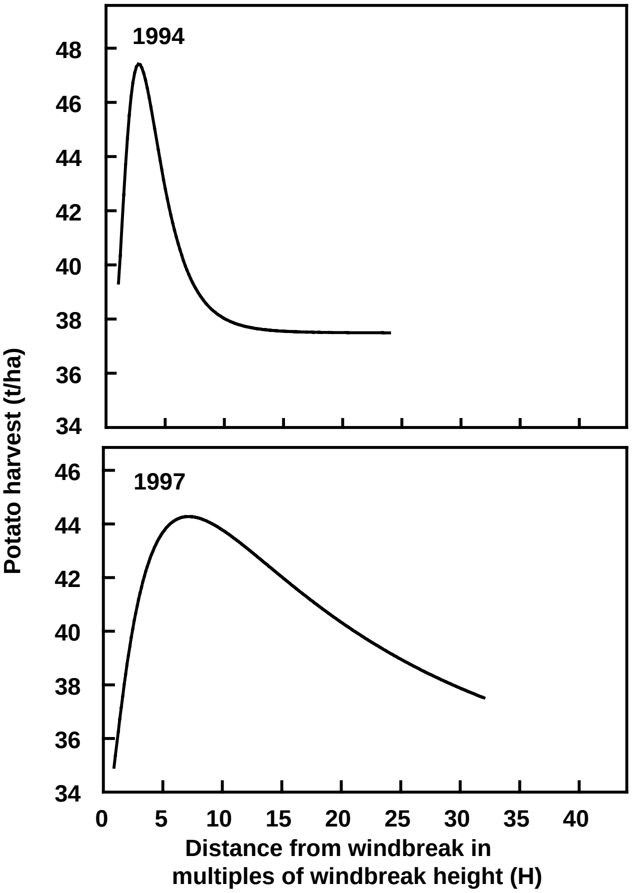

Figure 3. A log-normal regression model was fitted to the potato yield data where significant differences in yield with distance from the windbreak were observed (replicate 2 in 1994, and replicate 1 in 1997).

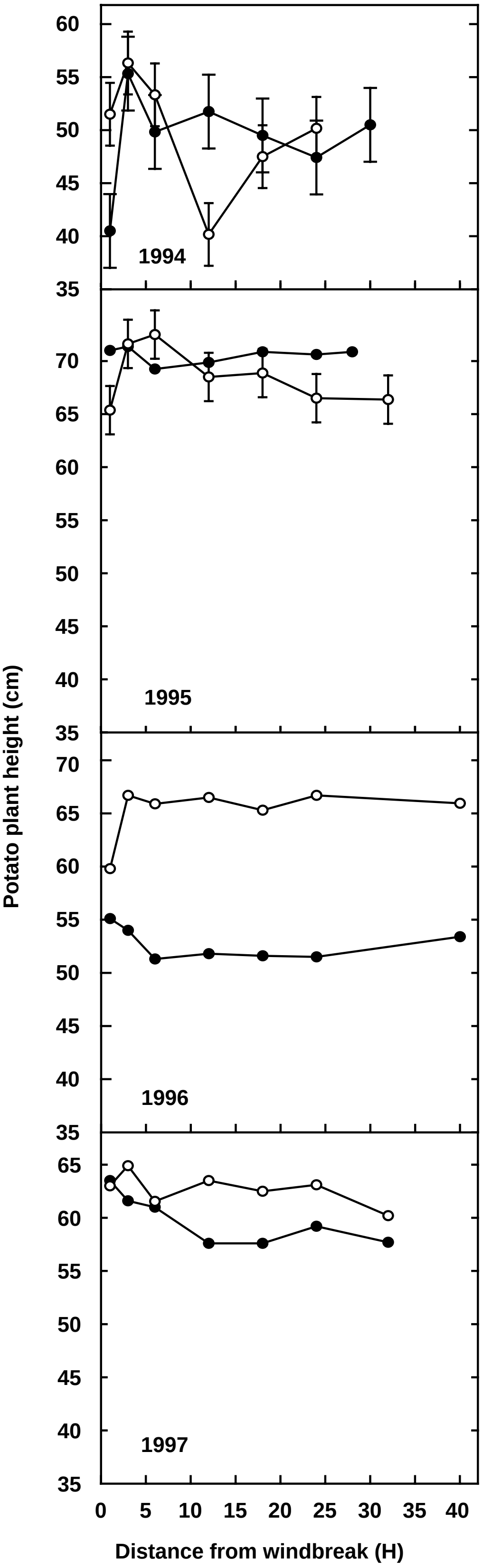

Figure 4. Potato plant height (● replicate 1, ○ replicate 2) at several distances from the windbreak. Vertical bars indicate the l.s.d. at $P = 0.05$.

Plant height

Differences in potato plant height with distance from the windbreak were only significant in 1994 (both replicates) and 1995 (replicate 2) (Fig. 4). Plant height did not correlate with yield in 1994; however, plant height was weakly correlated with yield in replicate 2 in 1995. Height and yield showed no correlation in 1996 or 1997.

There were significant differences in leaf number in 1994 (replicate 2) and in 1995 (replicate 2); however, the observed differences could not be attributed to the effect of the windbreak (Fig. 5). Leaf number was not correlated with potato yield.

Leaf damage

There was a significant trend of increased leaf damage with increased distance from the windbreak (Fig. 6). The bulk of leaf damage was minor although moderate and severe damage generally increased with distance from the windbreak. In 1996, there was less total leaf damage and the proportion of moderate and severe damage was much lower than in 1995 or 1997. The total amount of moderate and severe leaf damage was significantly lower in 1996 (0.071%) than in either 1995 (1.811%) or 1997 (1.529%).

Sigma-Plot was used to test the correlation between observed yield and damage for each replicate between 1995 and 1997. The depression in yield that could be attributed to competition with the windbreak (1–3 H) was omitted from the data sets to be tested for correlation. Total damage was significantly and negatively correlated with yield in 1995 (replicate 2) and 1997 (replicate 1) (Fig. 7). Total damage also had a negative (but not significant) correlation with yield in 1995 (replicate 1), and 1997 (replicate 2). The percentages of moderate and severe leaf damage were combined, and this was significantly and negatively correlated with yield in 1995 (replicates 1 and 2) and in 1997 (replicates 1 and 2) (Fig. 8). Neither total nor moderate to severe damage was correlated with yield in 1996.

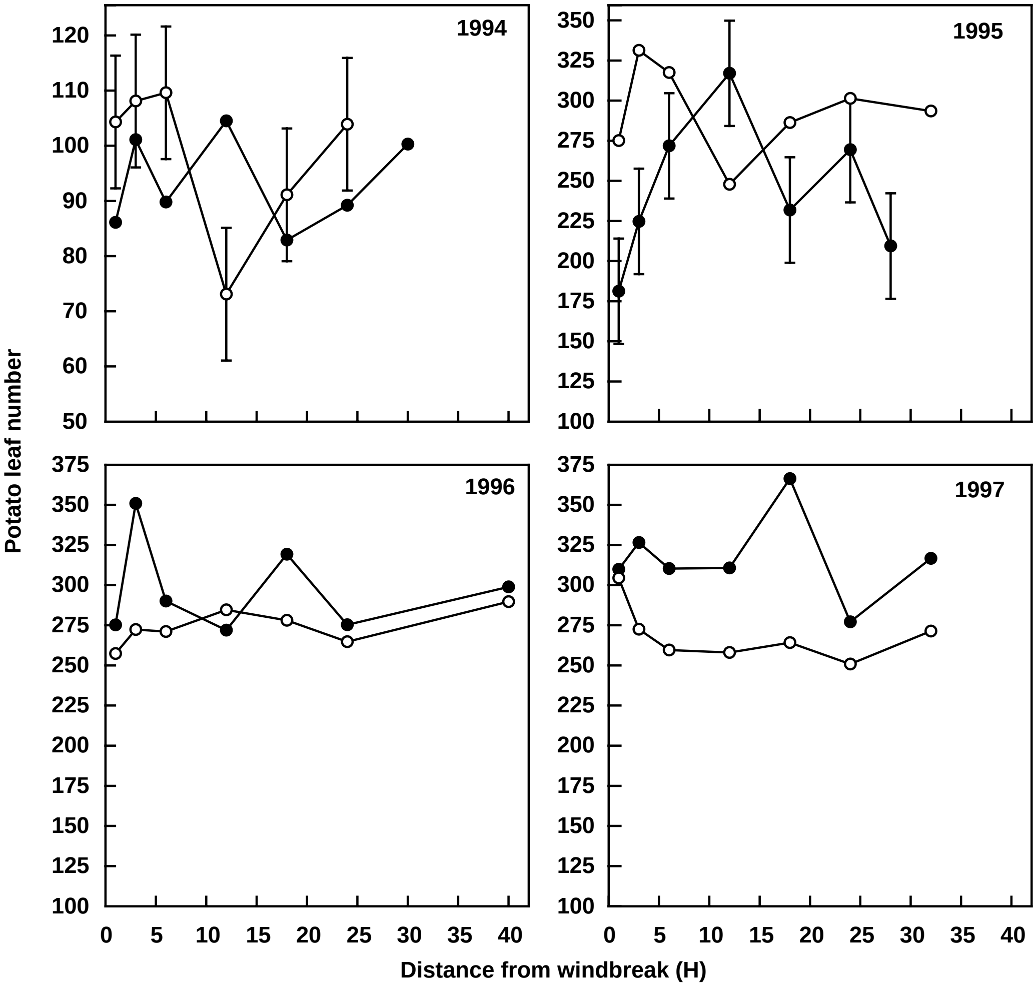

Figure 5. Potato leaf number (● replicate 1, ○ replicate 2) at different distances from the windbreak. The 1994 data are at the 8-week stage; the data in 1995, 1996 and 1997 were at flowering (12–14 weeks). Vertical bars indicate the l.s.d. at $P = 0.05$.

Discussion

Mechanisms for increased yield

In potatoes, a significant increase in yield was observed between 3 and up to 18 times the height of the windbreak. Sun and Dickinson (1997) found that a critical exponential model best fitted the significant 1994 potato data presented here. The data were reanalysed using both the critical exponential model and the log-normal regression model. The log-normal regression model better described changes in yield in 1994 ($R^2 = 0.63$ compared with 0.26 for the critical

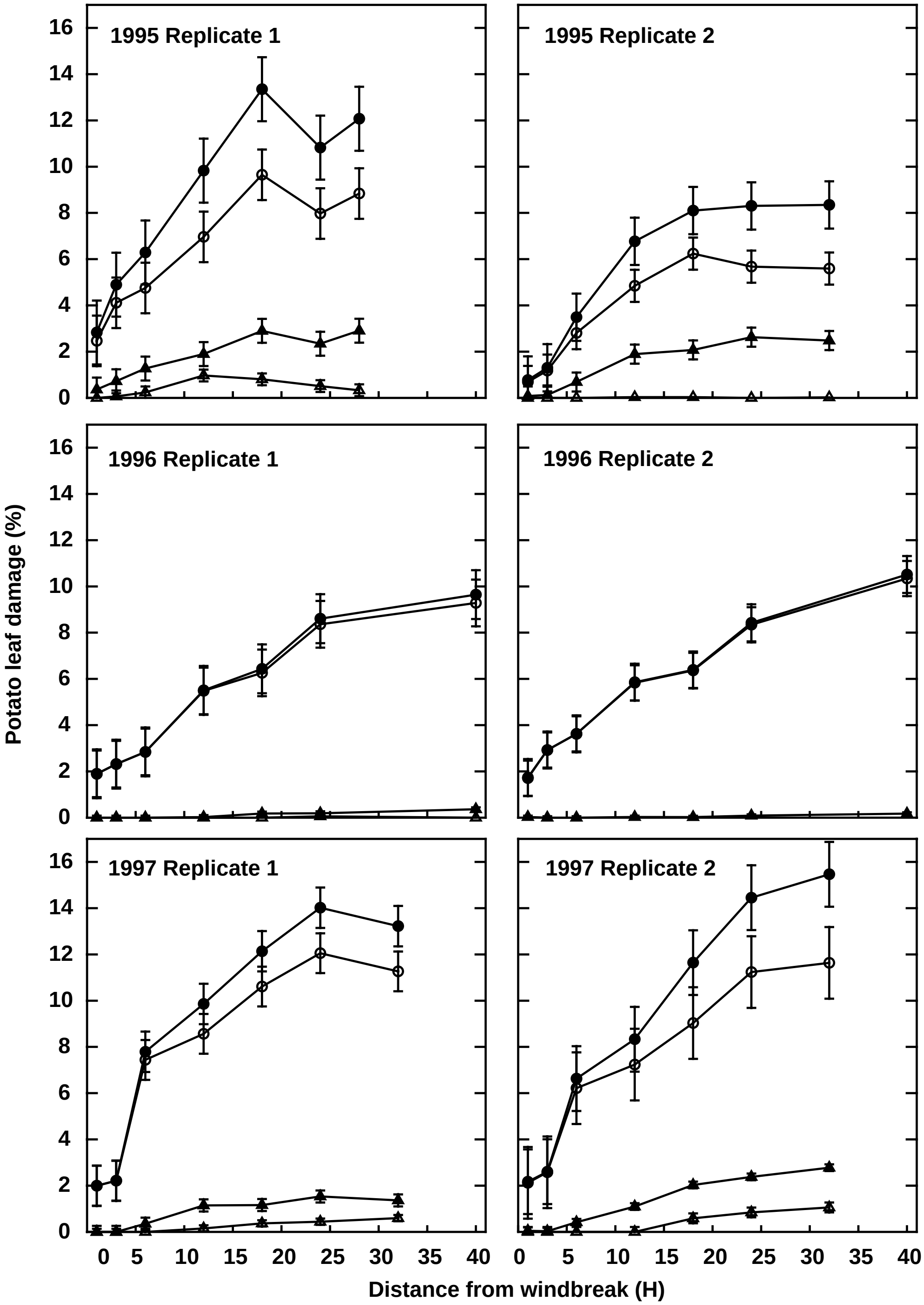

Figure 6. Potato leaf damage (● total, ○ minor, ▲ moderate, △ severe) at different distances from the windbreak in 1995, 1996 and 1997. Vertical bars indicate the l.s.d. at $P = 0.05$.

exponential model), and was applied to the significant yield data from 1997 ($R^2 = 0.40$ compared with 0.32 for the critical exponential model).

Sun and Dickinson (1997) reported differences in plant height associated with a windbreak effect, and commented that plant height and leaf number increased rapidly between 2 and 6 weeks from planting, but that height growth and leaf production slowed between 6 and 8 weeks as the crop reached maturity. There was a similar pattern in 1995, 1996 and 1997 (data not shown). Sun and Dickinson (1997) concluded that plant height and leaf number were 2 important indicators of windbreak effectiveness. However, this study found that plant height and leaf number were generally not correlated with yield. Nevertheless, Sun and Dickinson (1997) suggested that plant height and leaf number might be more important during the growth period, rather than at plant maturity. Sun and Dickinson (1994, 1997) also concluded that the windbreaks increased potato size (proportion of A-grade potatoes) rather than overall quantity. However, subsequent harvests at this site found no significant difference in the proportion of A-grade potatoes with distance from the windbreak.

Drought stress is known to adversely affect the yield of potatoes (Costa *et al.* 1997; Karafyllidis *et al.* 1996). However, the crop was well watered throughout the period of study so water almost certainly did not limit crop growth.

The increase measured in potato yield was almost certainly due to reduction in the amount and severity of wind damage to potato leaves. In this study, the 1996 potato tuber yield was greater than for all other years. This was possibly

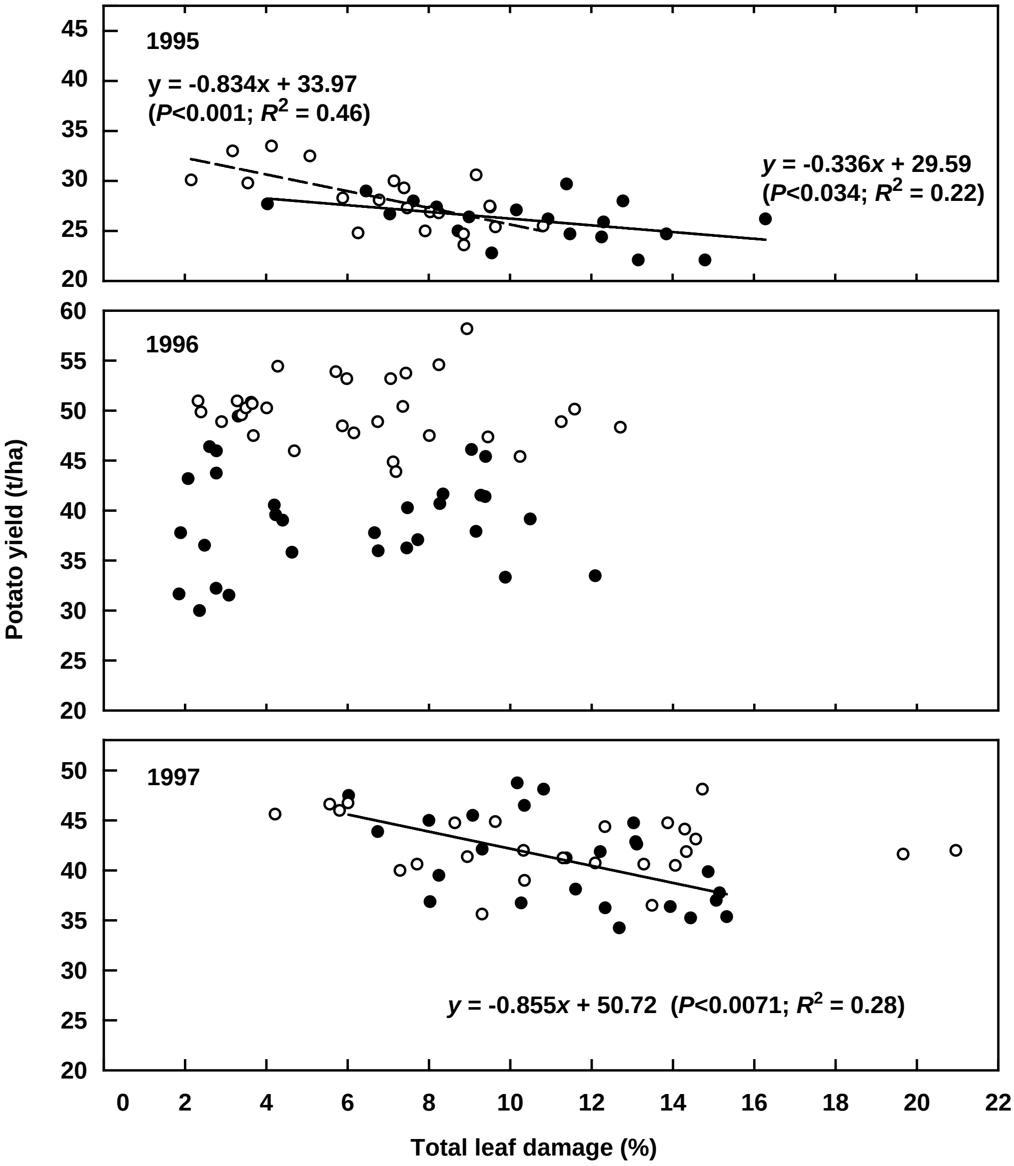

Figure 7. Correlation between potato yield and total leaf damage (● replicate 1, ○ replicate 2) for 1995–97.

due to the lower total leaf damage and lower proportions of moderate to severe leaf damage recorded in 1996 than in 1995 and 1997. Notably, the mean wind speed was significantly lower in 1996 than in all other years, which would have contributed to the lower moderate and severe wind damage levels recorded.

It has been noted previously that any observed increases in potato yield come as a result of a reduction in wind damage to leaves on plants afforded wind protection in addition to improved microclimatic conditions (Sun and Dickinson 1994, 1997). Engels and Marschner (1987) investigated the growth rates of potato during the phase of linear tuber growth and the effects of altering the size of the carbohydrate source and sink on tuber growth rates. Reducing the source strength by removing alternate leaflets or removing 1 of 2 equal-sized main stems per plant immediately reduced tuber growth rate per plant by 50%, and in most instances the same was true of individual tubers. This suggests that the removal of photosynthetic surface area of potato plants via leaf damage may have affected tuber growth in this study in a similar manner to that recorded by Engels and Marschner (1987). Yield reductions due to leaf damage have been noted in many other crops, including bananas (Tai 1977; Eckstein *et al.* 1996), citrus (Reuther 1977), melons (Schales 1984), rice (Lin *et al.* 1994) and strawberry (MacKerron, 1976).

Similar results for potatoes grown behind windbreaks were observed by Chaput and Tuskan (1990), in a field trial in North Dakota in 1989–90 where the potato yields increased with distance from the windbreak. However, Chaput and Tuskan (1990) assumed that yield at 10 H was

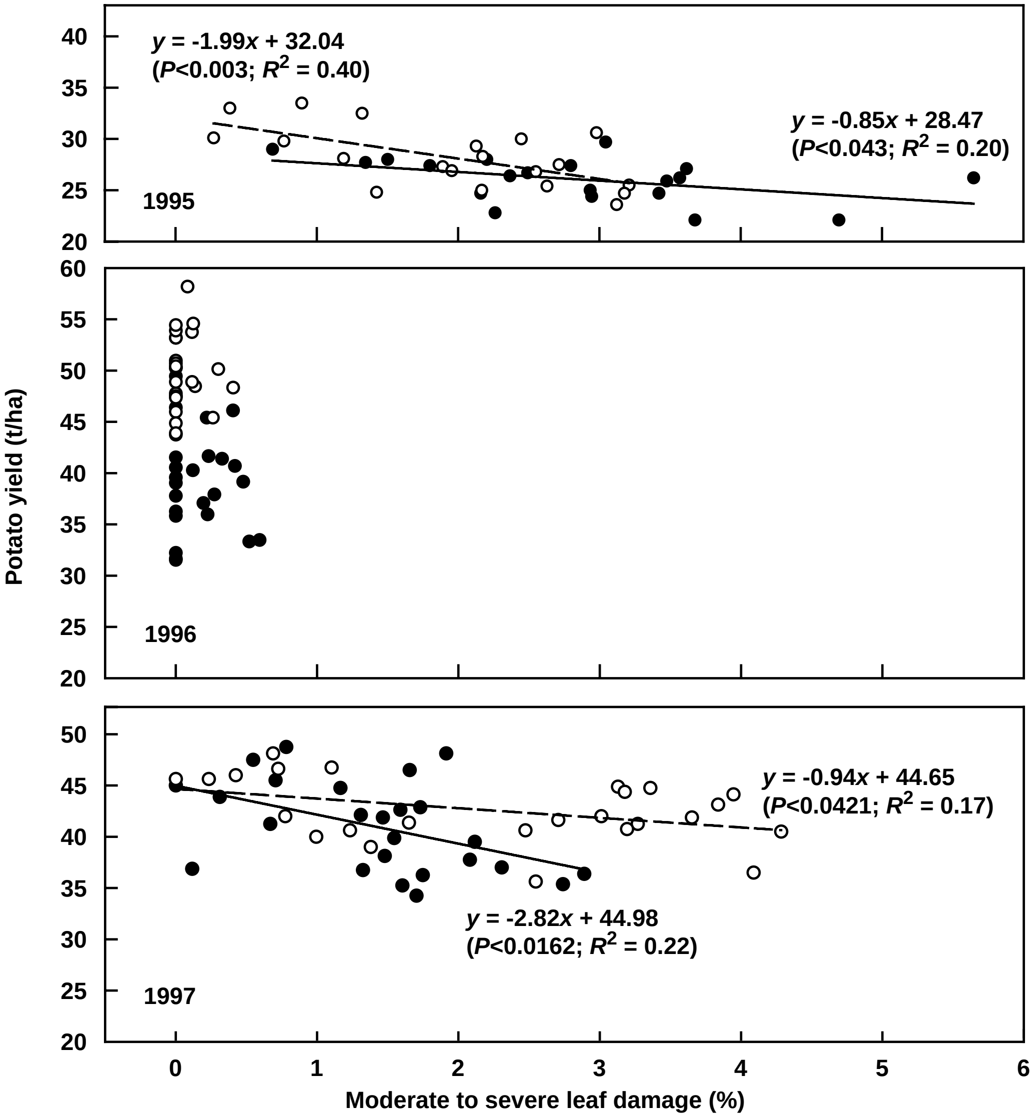

Figure 8. Correlation between potato yield and moderate and severe leaf damage (● replicate 1, ○ replicate 2) for 1995–97.

open yield and so may have overestimated open yield. If they had assumed that unsheltered yield was at 25–40 H, they may have recorded similar total yield increases to those found in this report.

Conclusion

The results from this study indicate that the incorporation of windbreaks into farming systems on the Atherton Tablelands may be beneficial in reducing potato leaf damage and possible yield losses in those seasons with high wind speeds, although results in this study were variable both within and between seasons. Potato leaf damage was negatively correlated with potato tuber yield in years where average wind speed exceeded 3.15 m/s. The average wind speed recorded between April and September at the site was 3.45 m/s (average annual wind speed was 3.68 m/s), which would suggest that, in an average year, windbreaks might reduce moderate and severe leaf damage in potato crops on the Atherton Tablelands. This reduction in leaf damage may then lead to increased potato tuber yield. The reduction in leaf damage measured for potatoes suggests that windbreaks may also benefit orchardists in the area by improving fruit quality, if not yield.

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