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Abstract. **The effects of wind protection on growth and total and marketable yields of snap bean (*Phaseolus vulgaris* L.) planted at 2-week intervals through the 1994 and 1995 growing seasons were examined. Research was conducted under nonirrigated conditions at the Shelterbelt Research Area, Univ. of Nebraska Agricultural Research and Development Center (ARDC) near Mead. 'Strike' (white-seeded) and 'Rushmore' (dark-seeded) were planted in locations sheltered from wind stress by tree windbreaks (shelterbelts) and in locations exposed to normal winds using a randomized complete-block design with a split-split plot arrangement of treatments. Air temperature, soil temperature, humidity, wind speed, and wind direction were monitored. Detailed microclimate conditions at bean canopy level in sheltered and exposed plots are provided in the text. Wind speed in sheltered areas averaged 36% of open field wind speed in 1994 and 43% of open wind speed in 1995. Soil temperatures were higher in sheltered areas than in exposed areas. Microclimate changes due to shelter had no effect on the percent seedling emergence or number of days to emergence. Plants in shelter had significantly higher total dry weight and leaf area index and greater total internode length than exposed plants. Both total and marketable yields were increased significantly by production under sheltered conditions each year. Planting date and cultivar also had a significant impact on average pod yields. No interactions between shelter and planting date, or shelter and cultivar, were found in either year. The results suggest that wind protection provided by shelterbelts (tree windbreaks) can increase pod yields of snap bean both early and late in the season. This may result in greater profit for the grower due to a tendency for higher prices at these times.**

Snap beans are a warm-season crop with little frost tolerance and very low tolerance to physical damage from wind and wind-blown soil (Finch, 1988). Investigations of shelter effects on crop production attempt to predict quantitatively the effect of reduction of wind speed by barriers on microclimate and crop performance. Once emerged, the sheltered crop interacts with and modifies the microclimate (Rosenberg et al., 1983). In snap beans, the harvest is of primary interest, and earliness to market is directly related to price (Neild and Greig, 1972). Harvest duration is of major economic importance to maximize the time in the market. Many aspects of the role that shelter plays in snap bean growth and production have been studied (Bagley, 1964; Bagley and Gowen, 1960; Rosenberg, 1966, 1967; Shah, 1962), but its influence with variation in planting date and cultivar are yet to be determined. This research was undertaken to relate specific environmental factors in sheltered and exposed locations to changes in snap bean growth and development, to study the influence of planting date on the total and marketable pod yields of two cultivars grown under sheltered and exposed conditions, and to quantify yields and financial benefits obtained from snap beans grown under the two systems.

Materials and Methods

Snap beans were planted in the summers of 1994 and 1995 at the 259-ha Shelterbelt Research Area, Univ. of Nebraska Agricultural Research and Development Center, near Mead (41°29´N latitude, 96°25´W longitude, 354 m above sea level). The two treatments applied were wind sheltered and exposed with four replications of each treatment for a total of eight main plots each year. Snapbean plots in four independent, identical mature windbreak systems comprised the four randomized replications of the sheltered treatment. Each windbreak consisted of two rows of green ash (*Fraxinus pennsylvanica* L.), eastern red cedar (*Juniperus virginiana* L.), and Austrian pine (*Pinus nigra* Arnold), arranged as mixed pairs of the possible combinations. The average height and width of the shelterbelts during the study period were 13 and 14 m, respectively. In eastern Nebraska, the prevailing winds are mainly from the south or southwest during the growing season (May–September). Sheltered crops were planted between 1 and 2 H (H representing the height of the shelterbelts) leeward of four east–west oriented shelterbelts established in 1966. Vegetable plots were at least 7.62 m from either end of each shelterbelt to avoid wind eddy effects in this area. Exposed treatment plots were at least 15 H and not directly downwind from any shelterbelt. Both sheltered and exposed plots were 650 m^2 in 1994 and 1115 m^2 in 1995. The soil is Typic Arguidoll (Sharpsburg silty clay loam recently reclassified in the Aksarben series).

Microclimate conditions in each of the eight main plots were monitored by measuring wind speed, air and soil temperatures, relative humidity (RH) using an automated CR10 data logger (Campbell Scientific, Logan, Utah) in each plot area for a total of eight datalogger systems. Each datalogger system included an air temperature/relative humidity sensor, an anemometer for wind speed and a wind direction sensor. Cup anemometers (model 12102; R.M. Young, Traverse City, Mich.) were used to measure wind speed at a height of 0.5 m aboveground. Air temperature and RH were measured at 0.4 m height using temperature and RH probes (models HMP35 and CS500; Campbell Scientific). Most research on plant response to wind stress has used sensors only at the standard meterological height of 3 m. Since wind speed is reduced by friction at ground level, we selected 0.5 m as more comparable to snap bean crop canopy height. The anemometer and AT/RH sensors were located on the north edge of the plots, adjacent to the last bean row farthest from the windbreak, at half the length of the vegetable plot, and at comparable distance from the last row in the exposed plots. Due to leaf interference when the canopy closes, the anemometer cannot actually be in the plant rows. Temperature probes were calibrated to ±0.5 °C accuracy each year. Humidity sensors were calibrated to ±2% accuracy each year. Microclimate data were measured every minute, with hourly and daily averages recorded. Soil temperature was measured using soil thermocouple probes (TCAV, Campbell Scientific) at 7.5 cm. Soil water was measured weekly throughout the study by the gravimetric method. Ten soil samples to a depth of 30 cm were randomly collected each week for each planting within each plot, then mixed and subsampled. Plots were not irrigated.

Two snap bean cultivars, 'Strike' and 'Rushmore' (Seminis, Oxnard, Calif.), were used for the study. 'Rushmore' is a dark-seeded bean while 'Strike' is white-seeded. In 1994, seven plantings were made from 25 Apr. through 2

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Aug. Due to excessively wet soils in 1995, only six plantings were made from 18 May to 25 July. Nitrogen (67.2 kg·ha^{-1}) was applied each year at each planting date. No additional fertilizer was applied. Pendimethalin (Prowl 3E; American Cyanamid, Princeton, N.J.) was applied at 1.7 kg·ha^{-1} a.i. for weed control with subsequent hand hoeing. The insecticides esfenvalerate (Asana XL; DuPont, Wilmington, Del.) and carbaryl (Sevin; Rhone-Polenc, Research Triangle Park, N.C.) were used to control bean beetles. Plantings were made about every 2 weeks, oriented perpendicular to the shelterbelts (or equivalent unsheltered area) and randomized within the plot, each planting forming subplots within the replicated main treatment plots of wind exposed or sheltered. In-row spacing was 7.6 cm at a depth of 1.9 to 2.5 cm. In 1994, four 15-m rows, each 76 cm apart, of each cultivar were planted, with the center two rows used for sampling. In 1995, eight 15-m rows, 76 cm apart, were planted with the inner six rows used for sampling to increase total weight of each sample.

For each planting, percent emergence and days to emergence were recorded. Plant samples for growth and development measurements were taken at the developmental stages of V3 (first trifoliate), V4 (third trifoliate leaf), R5 (pre-flowering), R7 (first pod), and R8 (pod fill) based on (Gepts, 1987). In 1994, samples were taken at the first three developmental stages as in 1995 plus at the R7 (pod wall growth) stage rather than at R8. These data were collected for planting dates 3 (23 May), 4 (10 June), 5 (5 July), and 6 (19 July) in 1994 and for planting dates 1 (18 May), 3 (13 June), and 5 (11 July) in 1995. Data collected included dry weight of leaves and stems, plus total internode length and leaf area.

Yield per plant was determined by hand harvesting four 91.5-cm sections randomly assigned from the center rows of each plot for each cultivar. Sheltered and exposed plots were harvested the same day. The number of plants within the row segments assigned for each yield determination was recorded. Pod yield (g/plant) was determined for each subplot and cultivar at each harvest. Pods were separated by sieve sizes, counted and weighed. At the end of the season, accumulated total pod yields were calculated and compared between each main treatment (sheltered vs. exposed), planting date, and cultivar. Pods of sieve size 3 (7.6 to 8.5 mm diameter) and 4 (8.6 to 9.9 mm diameter) were considered to be marketable for the purpose of this study.

Crop values were estimated from extrapolated marketable yields and the Chicago Wholesale Market prices of 'Round Beans Machine Picked' on the USDA Wholesale Vegetable Report (USDA/AMS, 1994, 1995) for the Monday closest to the harvest date.

Data were analyzed using a split-split plot randomized complete-block design with four replications. Main plots were two treatments, sheltered and exposed. Split-plots were planting dates and split-split-plots were cultivars. Analysis of variance procedures were performed on growth and yield data using the general linear model (GLM) of SAS (SAS Institute, Inc., 1985). Plant growth parameters were tested at each sampling stage for treatment, planting date, and cultivar. The differences in environmental parameters between sheltered and exposed treatments were tested using a two-sample paired t test. The leaf area index (LAI) was calculated as leaf area divided by ground area. Air and soil growing degree days (GDD) were computed by the formula:

$$GDD = \sum(\text{mean daily air or soil temperature} - \text{base temperature})$$

where the base temperature was 15.5 °C and the mean daily temperature was the average of the daily maximum and the daily minimum.

Table 1. Daily averages of environmental factors based on hourly averaged data from planting to harvest for each snap bean planting in sheltered and exposed locations in 1994 and 1995.

Environmental factor	Planting no.[z]	1994 Sheltered	1994 Exposed	1995 Sheltered	1995 Exposed
Wind speed (m·s^{-1})	1	0.83	2.12	0.86	1.81
	2	0.76	1.91	0.70	1.60
	3	0.75	1.68	0.65	1.61
	4	0.64	1.60	0.64	1.63
	5	0.58	1.52	0.64	1.65
	6	0.60	1.81	0.66	1.73
	7	0.62	1.87		
Air temp (°C)	1	19.62	19.05	20.85	21.06
	2	22.16	21.84	23.47	23.53
	3	23.01	22.75	24.93	24.80
	4	23.23	22.88	24.95	24.81
	5	23.36	22.18	23.74	23.58
	6	21.45	21.32	22.92	22.73
	7	18.93	18.96		
Soil temp (°C)	1	24.10	22.47	26.10	24.47
	2	26.07	24.15	28.79	27.36
	3	27.22	25.34	30.18	28.56
	4	28.14	26.30	30.11	28.17
	5	28.29	26.24	29.47	27.42
	6	27.50	24.83	28.82	26.60
	7	24.18	21.60		
Relative humidity (%)	1	70.67	72.59	71.80	69.35
	2	70.87	72.76	70.97	68.25
	3	74.40	76.56	68.68	66.41
	4	77.03	79.82	72.26	70.14
	5	77.44	80.58	72.58	70.70
	6	75.42	78.91	73.84	72.16
	7	76.56	79.19		
Soil moisture (%)	1	18.77	18.67	17.33	17.15
	2	18.68	18.56	14.28	14.05
	3	18.26	18.25	14.76	14.15
	4	17.86	18.27	10.95	10.86
	5	15.26	14.77	9.57	9.48
	6	15.16	14.77	9.48	9.56
	7	15.45	15.15		

[z]Planting number reflects data for the respective growing period for each planting: 1994: 1) 25 Apr.–4 July; 2) 9 May–8 July; 3) 23 May–18 July; 4) 10 June–3 Aug.; 5) 5 July–24 Aug.; 6) 19 July–24 Sept.; 2 Aug–9 Oct. 1995: 1) 18 May–17 July; 2) 30 May–7 Aug.; 3) 13 June–10 Aug.; 4) 27 June–9 Sept.; 5) 11 July–23 Sept.; 6) 25 July–23 Sept. (incomplete due to frost).

*,**,***Exposed is significantly different from sheltered at P = 0.1, 0.05, and 0.01, respectively.

Results and Discussion

The microclimate induced within the sheltered areas differed from that of the exposed areas during both years (Table 1). The differences were not, however, identical during the 2 years. Mean seasonal wind speeds in shelter were significantly reduced in both years and each planting period. When compared on a seasonal basis, sheltered wind speeds were 36% of open field wind speeds in 1994 and 43% of open field wind speeds in 1995. Seasonal average air temperatures did not differ between sheltered and exposed treatments in either year. The effects of shelter on relative humidity differed in 1994 and 1995. In 1994, mean seasonal relative humidity was higher in exposed areas than sheltered areas. The reverse was true in 1995. Mean soil moisture in 1995 was considerably lower than in 1994 due to lack of midseason rainfall. Based on seasonal averaging during each planting period, there were no differences in soil moisture between sheltered and exposed areas in 1994 with the exception of the 13 June planting date in 1995 when soil moisture in sheltered areas was higher.

In both years, mean weekly wind speeds in shelter were consistently lower throughout the growing season (Fig. 1). The maximum wind speed reduction occurred when the wind was perpendicular to the line of the windbreak. Minimum sheltering effects were recorded in week 7 in 1994 when easterly winds predominated. In both sheltered and exposed areas, average wind speeds at night were lower than during the day, with highest winds recorded at ≈1400 HR in both treatments (Fig. 1). The sheltered areas rarely experienced wind speeds in excess of 4 m·s^{-1} (Table 2), a common threshold wind speed for damage to a number of crops (Finch, 1988).

HortScience (August 2004) 39(5): 996-1,004.

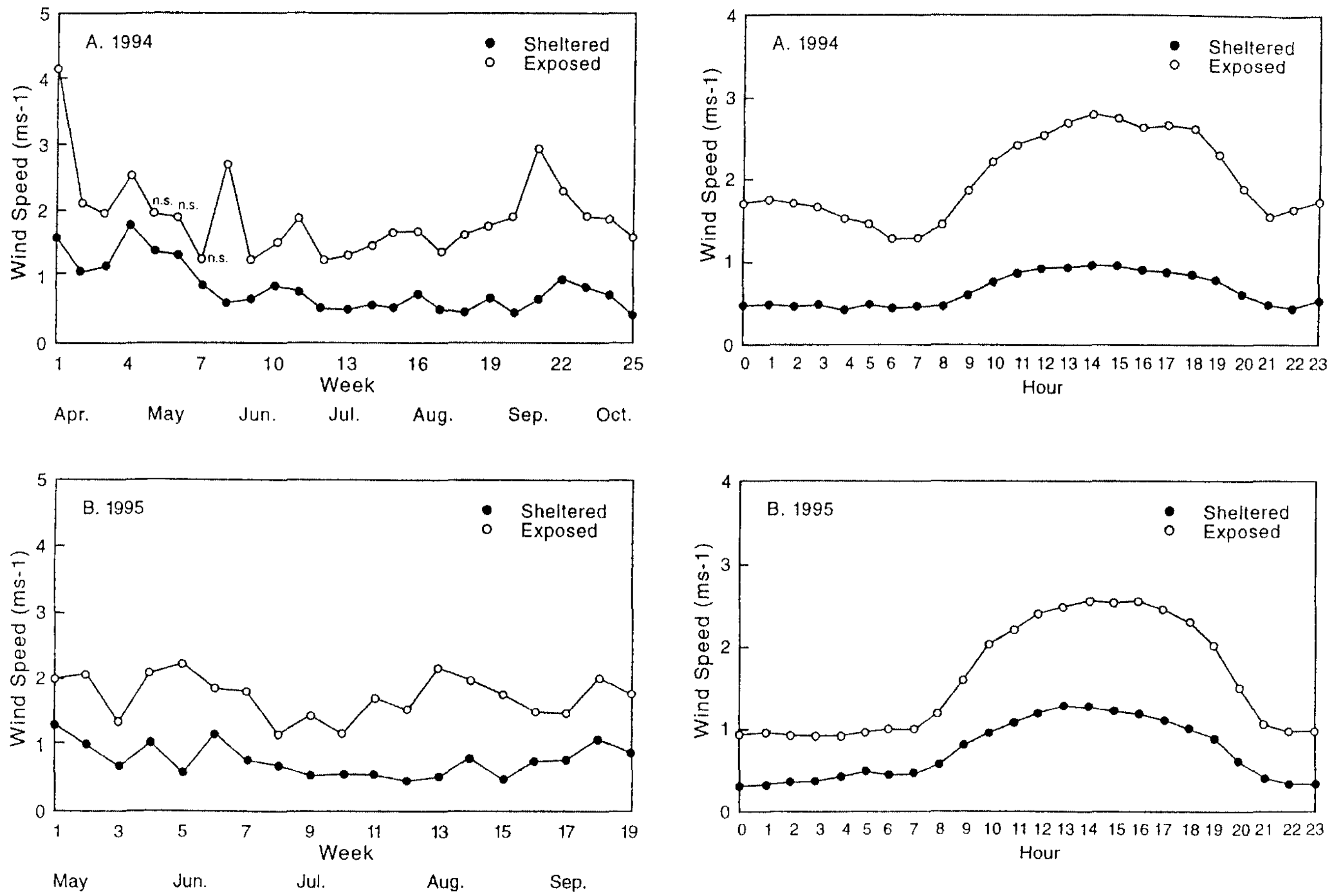

Fig 1. Average weekly wind speeds and full-season diurnal wind velocity patterns at canopy height (45 cm) for snap beans exposed to wind or sheltered by tree windbreaks in 1994 and 1995. [ns]Nonsignificant at $P = 0.05$. Diurnal wind speed hourly averages in sheltered and exposed locations were significantly different ($P = 0.05$) at all data points.

Table 2. Accumulated hours of three levels of wind speed (μ) from planting to harvest in sheltered (S) and exposed (E) conditions during 1994 and 1995.

	Planting dates 1994													
Wind speed (μ)	25 Apr.		9 May		23 May		10 June		7 July		19 July		8 Aug.	
($m·s^{-1}$)	S	E	S	E	S	E	S	E	S	E	S	E	S	E
2 ≥ μ > 0	1378	860	1247	780	1153	819	1176	852	1207	791	1594	931	1771	993
4 > μ > 2	155	574	68	509	66	434	39	384	17	388	38	563	53	676
μ ≥ 4	14	258	4	175	4	115	2	108	0	45	0	138	0	155
Total hours	1547	1692	1319	1464	1223	1368	1217	1344	1224	1224	1632	1632	1824	1824
Missing hours	157	12	145	0	119	24	127	0	0	0	0	0	0	0

	Planting dates 1995									
	18 May		30 May		13 June		27 June		11 July	
	S	E	S	E	S	E	S	E	S	E
2 ≥ μ > 0	1297	858	1538	1038	1356	985	1724	1175	1701	1160
4 > μ > 2	151	527	94	564	60	405	75	559	87	536
μ ≥ 4	3	66	0	30	0	26	1	66	1	93
Total hours	1451	1451	1632	1632	1416	1416	1800	1800	1789	1789
Missing hours	0	0	0	0	0	0	0	0	0	0

Based on seasonal averages, there were no clear differences in air temperature between sheltered and exposed treatments in either year. However, there were differences in the diurnal pattern of air temperature when data were separated into specific planting periods (Fig. 2). Based on planting date period averages, air temperature in sheltered plots was slightly higher in the late morning and early afternoon with maximum differences of ≈1 to 2 °C occurring from 1600 to 1700 HR. These differences were significant for PD 3, 4, and 5 in 1994. Based on both seasonal and planting period averages, night air temperature was slightly, but not significantly, higher in exposed areas than in sheltered areas in each year.

While the differences in diurnal air temperature between sheltered and exposed treatments were small, the differences in diurnal soil temperature patterns are quite distinct. Soil temperature in the sheltered areas was 1 to 4 °C higher than in the exposed areas for each planting throughout the growing season during both 1994 and 1995 (Table 1). Diurnal soil temperatures were significantly higher in sheltered areas at all times of day and night in 1994 and during the late night and early morning hours in 1995 (Fig. 3).

Based on seasonal averages, weekly mean relative humidity was higher in exposed areas than sheltered areas for the majority of production periods in 1994 (Fig. 4). In contrast, there was a tendency for the relative humidity to be higher in sheltered plots throughout the growing season in 1995. Numerous studies of the effect of shelter on diurnal patterns of relative

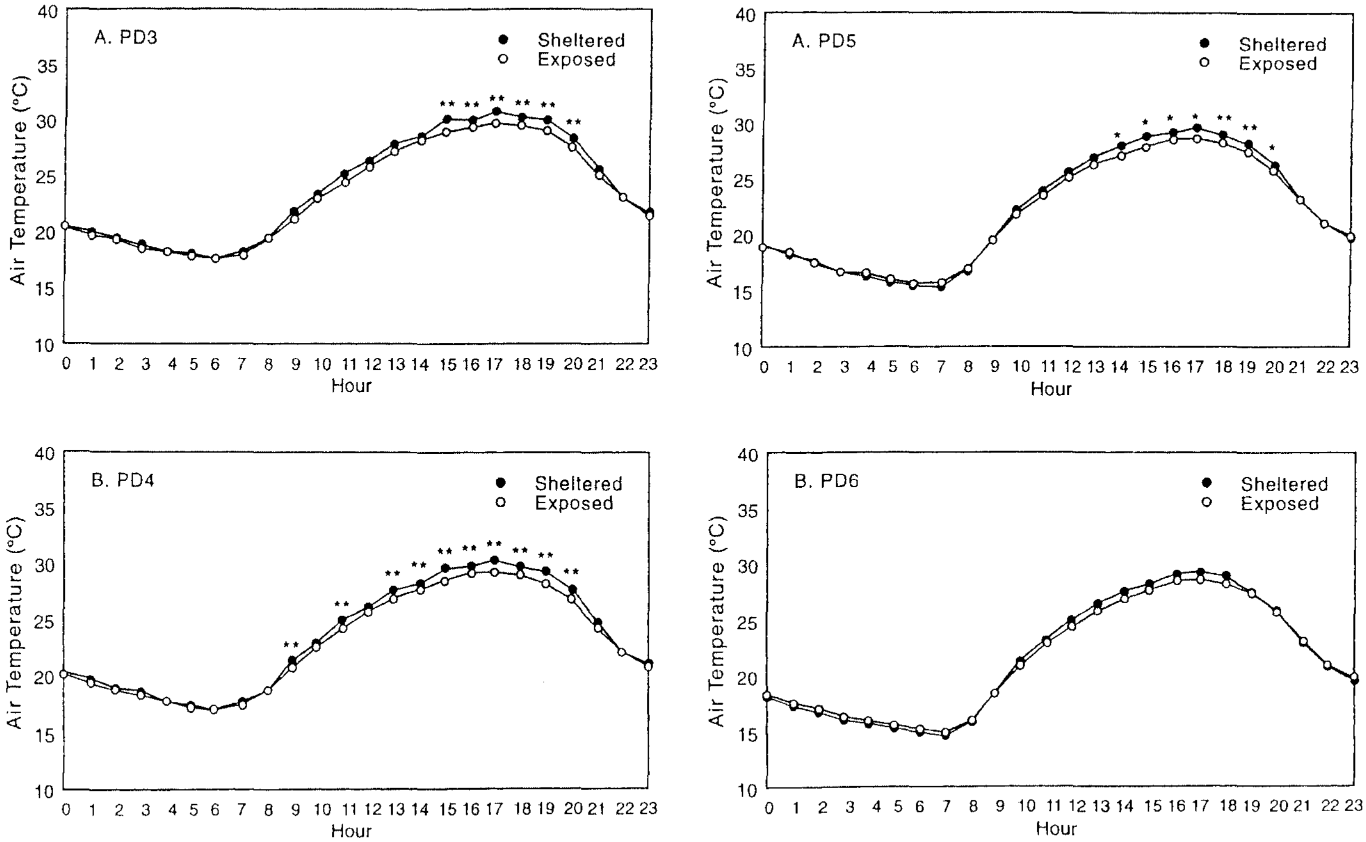

Fig. 2. Full-season diurnal pattern of average hourly air temperature at 45 cm in sheltered and exposed snap beans for planting dates 3, 4, 5, and 6 in 1994. *,**Significant differences between sheltered and exposed data at $P = 0.1$ and 0.05, respectively.

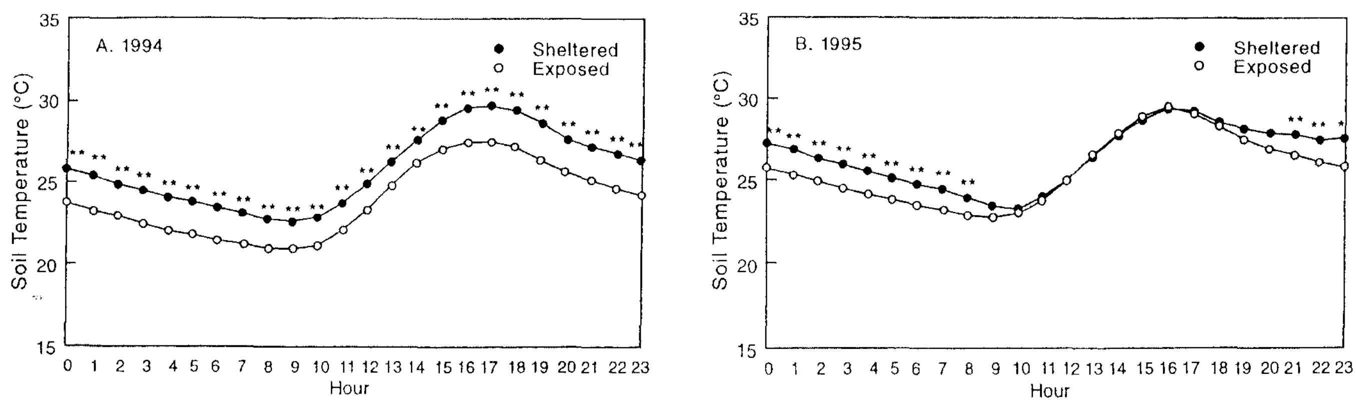

Fig. 3. Full-season diurnal pattern of average hourly soil temperature at 7.5 cm in sheltered and exposed snap bean crops in 1994 and 1995. *Significant at $P = 0.05$.

humidity have indicated that mean relative humidity was generally higher in shelter both during the day and night (Rosenberg et al., 1983; van Eimern et al., 1964). According to Rosenberg et al. (1983), despite the increased temperature, RH in shelter is generally higher. The difference in RH between sheltered and exposed areas is even greater at night when air temperature in sheltered areas is lower. Data recorded in 1995, a dry year, support these generalizations; data from 1994, a wetter year, do not. RH in the sheltered areas was higher at night and lower in the day in 1994. In 1995, RH in the sheltered areas was always higher than or equal to the RH in the exposed areas (Fig. 4). This may reflect the variability of windbreak microclimate with season.

In 1994, soil moisture was >14% throughout the season. In 1995, soil moisture gradually declined throughout the season reaching a minimum of 9% at week 11 (3–10 Aug.; Fig. 5). At these levels, plants were moisture stressed as the patterns of rainfall, and hence soil moisture, affected growth and yield.

Rainfall was distributed more uniformly through the growing season in 1994 than in 1995 (Fig. 5).

While air GDD_{15} was slightly higher in the sheltered areas than in exposed areas for all plantings in 1994 and 1995, the differences were nonsignificant ($P = 0.8$ and 0.7, respectively). However, the greater soil GDD_{15} for all sheltered plantings for both years was significant (Table 3). Among the planting dates, the accumulated heat units between planting and harvest increased as the season progressed though the fourth planting date. In both sheltered and exposed areas, the accumulated GDD_{15} was reduced for the fifth planting date in both years (5 July 1994 and 11 July 1995). This suggests a more rapid maturation rate for the mid- to late summer crop both years.

Plant growth. Shelter did not have an independent effect on the percent seedling emergence in either year ($P > 0.05$ and $P > 0.05$, respectively), but a significant interaction of treatment × planting date did exist each year ($P \leq 0.05$). It appears these interactions were related to significantly higher soil temperatures in the sheltered areas during these periods ($P \leq 0.05$, Table 3). Percent emergence ranged

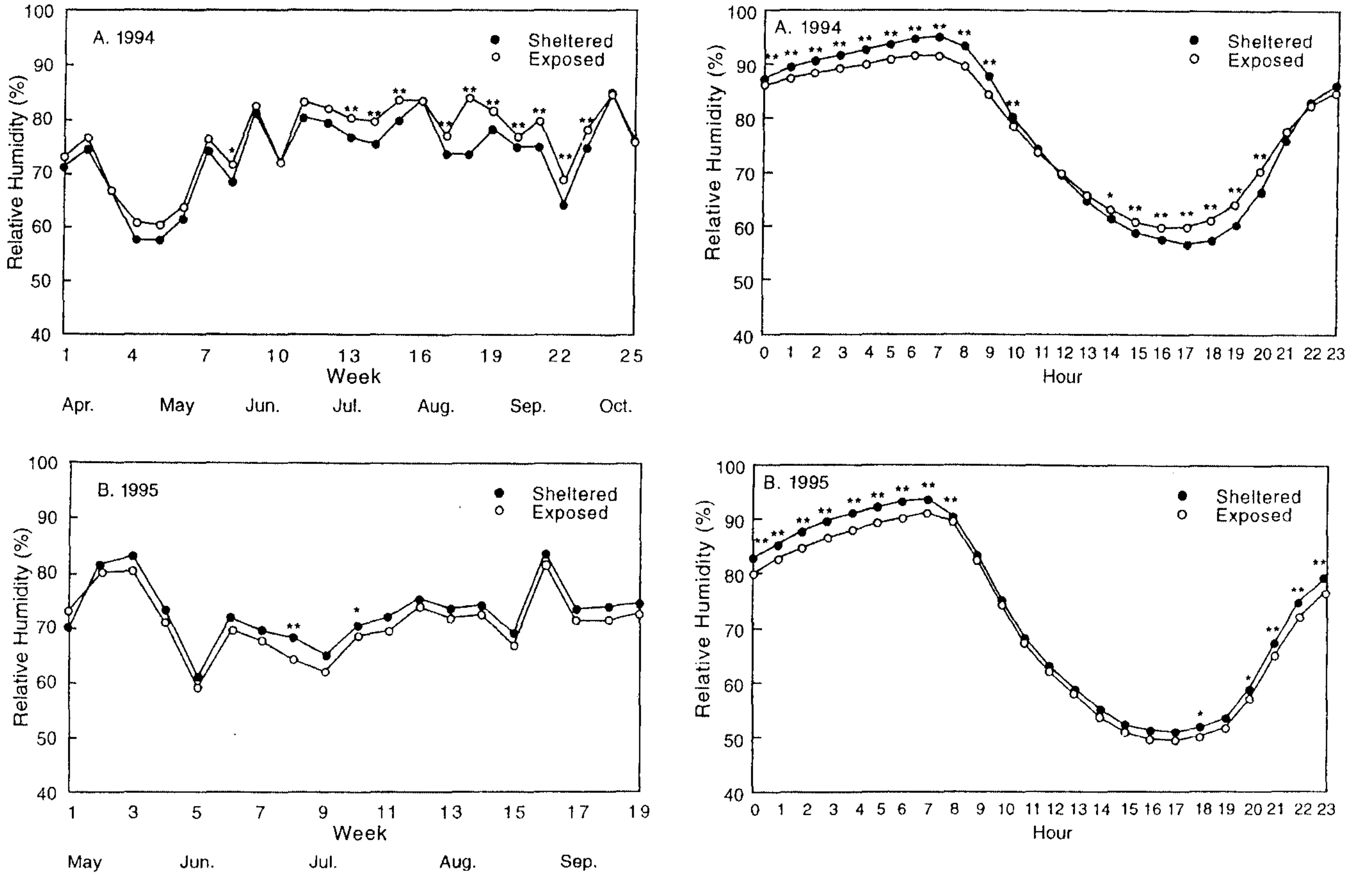

Fig. 4. Average weekly relative humidity and the full-season diurnal pattern of relative humidity at canopy height (45 cm) in sheltered and exposed snap bean crops in 1994 and 1995. *,**Significant at P= 0.1 and 0.05, respectively.

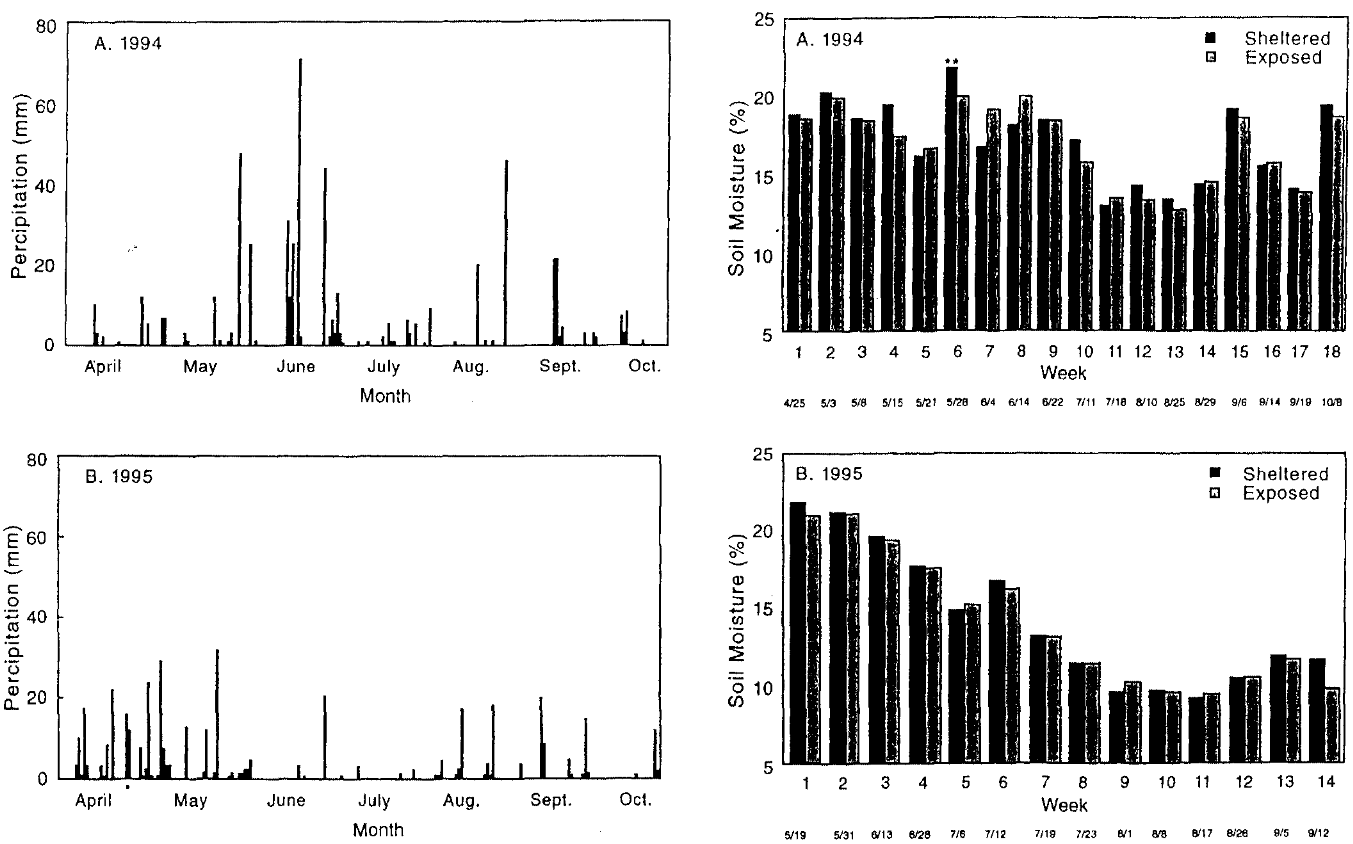

Fig. 5. Precipitation (rainfall) during snap bean production, 1994 and 1995 and the average weekly percent soil moisture in the top 0.3 m in snap bean crops sheltered or exposed to wind stress. **Significant at P = 0.05.

Table 3. Seasonal summaries of air and soil growing degree-days (GDD[z]) in areas sheltered and exposed to wind during the 1994 and 1995 growing seasons.

Year	Planting date	Days to harvest	Air GDD_{15} Sheltered	Air GDD_{15} Exposed	Soil GDD_{15} Sheltered	Soil GDD_{15} Exposed
1994	25 Apr.	71	392	375	607**	448
	9 May	62	411	398	637**	483
	23 May	58	427	412	662***	541
	10 June	55	500	483	819***	699
	7 July	51	347	338	650***	545
	19 July	69	410	400	814***	635
	8 Aug.	76	342	337	661**	482
	Full season	175	934	907	1628**	1246
1995	18 May	61	346	344	631*	524
	30 May	69	547	569	900**	790
	13 June	59	553	546	863**	766
	27 June	75	710	699	1092***	946
	11 July	75	661	649	1049**	900
	25 July[y]	60	487	476	799***	669
	Full season	128	907	891	1554***	1309

[z]Accumulated GGD using a base temperature of 15 °C from planting to harvest.
[y]Incomplete due to frost.
*, **, ***Significant at $P = 0.1$, 0.05, or 0.01, respectively.

Table 4. The days to and percentage of emergence of snap beans (average of two cultivars) in areas sheltered and exposed to wind.

Year	Planting date	Sheltered ST (°C)[y]	Sheltered Soil[z] GDD_{15}	Sheltered DTE[x]	Sheltered % Emergence[w]	Exposed ST °C	Exposed Soil GDD_{15}	Exposed DTE%	Exposed % Emergence
1994	25 Apr.	16.9	40.9	20	34.4	14.1	16.9	20	29.7
	9 May	19.3	31.1	9	60.4**	16.8	15.1	10	34.4
	23 May	27.0	67.2	8	77.8	23.4	47.5	8	68.8
	10 June	27.1	63.1	6	46.2	24.8	48.9	6	57.1
	5 July	27.9	87.5	10	25.9**	25.7	71.3	10	65.9
	19 July	29.0	177.0	14	31.6	27.5	156.0	14	42.5
	8 Aug.	28.3	75.0	7	76.2**	25.8	60.5	7	31.3
1995	18 May	18.9	36.4	12	78.6	17.7	25.1	12	60.3
	30 May	22.6	37.8	8	86.3	21.3	30.5	8	82.7
	13 June	30.2	92.1	7	76.0	26.9	70.6	7	74.8
	27 June	26.6	91.0	9	63.7	25.1	78.9	10	69.2
	11 July	32.2	234.3	14	30.3	30.9	217.1	14	36.8
	25 July	30.8	471.6	32	43.0	28.6	404.1	32	45.0

[z]GDD = growing degree days; accumulated GDD using a base temperature of 15 °C for the 7 d after planting.
[y]ST = Average soil temperature for the 7 d after planting.
[x]DTE = days to emergence.
[w]Based on 8 seeds/61-cm row.
**Significant at $P = 0.05$.

from 25.9 to 86.3 in sheltered areas and from 29.7 to 82.7 in exposed areas over the 2-year study (Table 4). Percent emergence was significantly greater in sheltered areas in the second and seventh planting periods in 1994 and was significantly greater in exposed areas in the fifth planting period of the same year.

Regression analysis indicated that the relationship between the percent emergence and soil GDD_{15} from the time of planting to first emergence was inconsistent between years (data shown in Table 4). In 1994, no significant correlation was found between the rate of emergence and soil GDD_{15} in either sheltered or exposed areas ($r = 0.34$, $P > 0.05$; and $r = 0.14$, $P > 0.05$, respectively). In the following year, there was a positive correlation between the percent emergence and soil GDD_{15} in sheltered ($r = 0.77$, $P = 0.07$) and exposed areas ($r = 0.89$, $P = 0.02$). The 1.2 to 3.6 °C difference in soil temperature from planting to final emergence between sheltered and exposed treatments substantiates the suggestion of vanEimern et al. (1964) that small differences in soil temperature may greatly influence the development of crops, especially in sprouting and the initial seedling development.

In general, shelter had no significant effect on the percent seedling emergence or the days to emergence of snap beans although the number of days to emergence decreased with each planting date each year due to more rapid accumulation of soil GDD_{15} ($P < 0.05$, $r = -0.81$ and $r = -0.77$, respectively).

Cultivars were significantly different in the number of days to first emergence in 1994 and the rate of seedling emergence in 1994 and 1995. The cultivar Strike had a significantly greater percent emergence than 'Rushmore' in the second, sixth, and seventh planting dates in 1994 and in the first planting date in 1995 (data not shown). Data from other planting dates did not show significant differences in emergence. In 1994 and 1995, the average seedling emergence over all locations and planting dates for 'Strike' was 52% and 63% as compared to 43% and 47% for 'Rushmore', respectively ($P < 0.02$ and $P < 0.01$). Dickson (1971) reported greater tolerance to *Pythium* root rots and greater cold soil germination associated with colored seed coats. Marx et al. (1972), Dickson (1971), and Deakin (1973) all found beans with colored seedcoats produced more vigorous seedlings than those with white seed. We were not able to corroborate any advantage in the colored seedcoat of 'Rushmore' in either early or late plantings of snap beans nor in any differential response to wind stress.

Total internode lengths were 2 to 6 cm greater under sheltered conditions, especially in the early (15 d) and late (55 d) development stages from the 10 June 1994 planting (data not shown). The greater elongation may be due to higher day air temperature and soil temperature in the sheltered areas (Kigel et al., 1991) associated with less wind, including less plant movement (Mitchell and Myers, 1995). Regression analysis between the accumulated air GDD_{15} and internode lengths for the June 10 planting in 1994 gave a correlation coefficient (r) of 0.97. In 1995, the r values for air GDD_{15} and total internode length for planting dates 1, 3, and 5 were 0.89, 0.98, and 0.99, respectively, indicating a strong correlation. The linear relationship was significant in each case ($P < 0.05$). In 1995, the decrease in internode lengths for the 11 July planting compared to earlier plantings (Table 5) most likely is related to water stress in both sheltered and exposed locations (Borst and Thatcher, 1987; Denmead and Shaw, 1959). Plant height increases induced by windbreaks have been reported for snap beans (Bagley and Gowen, 1960; Rosenberg et al, 1967), dry beans (Felch, 1964), as well as soybeans (Ogbuehi and Brandle, 1982; Radke and Burrow, 1970), wheat (Frank and Willis, 1978; Skidmore et al., 1974), oats (Sturrock, 1981), and cotton (Barker et al., 1985).

The effects of microclimate changes on the leaf area index (LAI) were similar to those found for total internode length. Plants from midseason (June) plantings had greater LAI than those planted either earlier or later in the season (data not shown). LAI was greater in sheltered areas, with this difference developing after the V4 growth stage (third trifoliate leaf) and reaching a maximum of 2-fold greater from shelter between 27 and 32 d after planting. The difference in LAI between sheltered and exposed beans gradually lessened to ≈1.5-fold greater in sheltered plants by harvest. This pattern for LAI development held each year. The opportunity for radiation interception and the amount of photosynthetic material contributing to crop growth is dependent on the LAI. Shelter significantly increased the amount of snap bean leaf material which may improve crop productivity.

The maximum LAI at pod-fill (R8 stage) in our later plantings was less than the LAI at pod-fill in earlier plantings, possibly reflecting a reduction in the rate of leaf expansion due to high temperatures (Lin and Markhart, 1996). In general, 'Rushmore' had greater LAI than 'Strike' when there was a significant difference between cultivars in response to planting date.

The total dry weight (total aboveground biomass) indicates the degree of efficiency of

Table 5. Comparison of total internode length, leaf area, and dry weight per plant between sheltered and exposed snap beans (average of two cultivars) at each sampling stage.

Planting date	SS[z]	DAP[y]	Total internode length (cm) Sheltered	Total internode length (cm) Exposed	Plant leaf area (cm^2) Sheltered	Plant leaf area (cm^2) Exposed	Plant total dry wt (g) Sheltered	Plant total dry wt (g) Exposed
1994								
10 June	V3	15	5.11**	2.91	42.48	27.35	0.23	0.24
	R5	35	9.62	7.47	208.13	56.80	3.35	2.51
	R7	47	22.11	16.03	240.56	170.04	0.52	11.10
	R8	55	60.49**	47.73	1394.96	1040.041	3.08	10.52
1995								
18 May	V3	27	3.67***	2.44	86.83***	42.75	0.58**	0.34
	V4	32	6.68***	4.26	266.87***	152.76	1.64***	1.04
	R5	43	22.19**	13.96	703.08**	453.18	4.98*	3.44
	R7	57	68.51***	42.14	1643.31**	1003.58	15.86***	10.10
	R8	61	79.10***	50.72	1313.07	1063.78	5.03	11.67
13 June	V3	17	4.41	2.34	81.77	79.82	0.47	0.52
	V4	23	5.77	5.30	256.75	230.59	1.53	1.56
	R5	37	45.01	38.40	1309.35**	1049.25	10.56	10.10
	R7	45	67.65**	54.87	1854.32**	1448.14	12.79	11.28
	R8	59	102.27	84.55	2653.37*	2057.72	25.10**	20.61
11 July	V3	29	3.41	3.33	91.711	01.03	0.55	0.71
	V4	38	19.30	21.27	256.86	367.80	1.79	1.82
	R5	52	30.10	17.05	1014.96	588.56	6.08	3.80
	R7	67	42.44	33.36	1056.02	949.28	10.66	10.01
	R8	75	(na)	(na)	(na)	(na)	25.00	34.59

[z]Sampling stage: V3 = first trifoliate; V4 = third trifoliate; R5 = pre-flowering; R7 = first pod; R8 = pod fill.

[y]Days after planting.

(na) = Data not available; beans not harvested due to frost damage.

*,**,*** Indicates sheltered is significantly different from exposed at $P \leq 0.1$, 0.05, and 0.01, respectively.

the plant in intercepting solar radiation and subsequent photosynthesis. In 1994, maximum total dry weight was obtained from the 23 May planting date, with later plantings on 10 June and 7 July having a progressive decrease in total dry weight. The leaf area data showed that the snap beans from the 23 May date had a greater leaf area than later plantings. In 1995, changes in snap bean total dry weight due to shelter were statistically significant for the 18 May and 13 June plantings ($P = 0.02$ and $P = 0.08$, respectively). Greater total dry weight in the 13 June date in 1995 may be a result of significantly greater mean soil moisture in sheltered areas than in exposed areas during this period.

Total pod yield data were averaged over planting dates from sheltered and exposed plants and the two cultivars to show the effect of shelter on snap bean yield (Table 6). Total pod yields were significantly higher from the sheltered areas than from the exposed areas both years (47% in 1994, 64% in 1995). This positive effect of shelter on total yield persisted throughout the growing season and the various planting dates. Total yields from sheltered beans were significantly greater than exposed beans in the first, fourth, and seventh planting dates in 1994 and in all five planting dates in 1995 (data not shown). The sixth planting date in 1995 was killed by frost before harvest. Overall yields were reduced 47% in 1995 compared to 1994, a reduction we attribute to the heat and drought stress during pod set in 1995 (Dickson and Boettger, 1984; Kigel et al., 1991; Konsens et al., 1991; Monterroso and Wien, 1990). In this non-irrigated study, it was impossible to separate the effects of heat and drought stress on pod set. The increase in total yield in sheltered areas may be attributed to the larger plants in the wind-protected plots, as indicated by significantly greater total internode lengths and greater leaf size .

Averaging the total yield data from both sheltered and exposed locations and from all planting dates (no significant interactions), the cultivar 'Rushmore' produced 57% more total yield than the cultivar 'Strike' in 1994 and 60% more in 1995 (Table 6). Differences in the response of cultivars might be produced by differences in sensitivity to environmental effects during various stages of plant development. Although 'Rushmore' did show small differences relative to 'Strike' in total internode length, leaf area and total dry weight, most of the differences between the cultivars were not statistically significant.

Analysis of marketable yields shows a similar trend to that of total yield (Table 6). Marketable pod yields were significantly increased by shelter in both 1994 and 1995 ($P < 0.05$). In 1994, marketable pod yield over the seven planting dates was 50% higher for sheltered plants than exposed plants, with significantly higher marketable yields during the first, fourth, and seventh planting dates. In 1995, sheltered plants produced 91% more marketable pod weight than exposed plants (Table 6). Planting date highly affected marketable pod yields each year ($P < 0.01$) with lower marketable pod yields in the earlier planting dates due to cold, wet conditions that retarded plant growth (data not shown). As temperatures became more favorable, yields gradually increased. However, air temperatures exceeded the optimum for snap bean production in the third planting in 1995 resulting in a split set. A portion of the snap bean pods were undeveloped and reduced marketable yield. The plants from this planting were taller, with greater LAI and total dry weight than from earlier or later plantings. Similar findings were obtained by Kigel et al. (1991) and Konsens et al. (1991) who found that heat stress in snap beans strongly reduced pod production with less effect on biomass accumulation.

The benefits of protecting vegetable crops from wind are often associated with earlier maturity, higher quality, and greater economic gain (Baldwin, 1988; Brandle et al., 1994). In this study, the production of snap beans in sheltered areas benefitted due to earlier maturation reflected in greater marketable pod yields. These yield increases, especially in the early-season planting dates, had a significant impact on the economics of snap bean production.

Economic value of windbreak. Market prices varied from week to week over the growing season and tended to be higher early and late in the season. In addition, the prices fluctuated depending on the weather conditions in major snap bean growing areas. For example, during the week of 8 July 1994, the wholesale price of beans increased from $14.00 to $22.00 per 30 lb (13.62 kg), mainly due to floods in Georgia that prevented harvesting in a major fresh market bean production area (Table 7).

Gross wholesale market value in 1994, calculated from marketable yield and price data, ranged from $8,939/ha on the fifth planting date to $1,469/ha on the first planting date (Table 7). Over seven planting dates during the 1994 growing season, a mean gross value of $6,100/ha was obtained from the sheltered crops compared to $4,163/ha from exposed crops. In 1995, wind protection resulted in substantial increases in the calculated gross market value of beans because of the higher proportion of marketable beans obtained from the sheltered sites. This increased value averaged $6,707/ha for sheltered areas compared to $4,125/ha from unsheltered areas.

To estimate the overall value of shelter to snap bean production, the costs associated with the windbreak must be considered. The

Table 6. Average yields of snap beans in areas sheltered and exposed to wind (averaged over planting dates and cultivars) in 1994 and 1995.

Year	Avg yield (g/plant) of two cultivars and all planting dates: Total Sheltered	Total Exposed	Marketable Sheltered	Marketable Exposed
1994	61.3*	41.8	32.8*	21.9
1995	33.9**	20.7	14.2**	7.4

Year	Avg yield (g/plant) of sheltered and exposed locations and all planting dates: Total Strike	Total Rushmore	Marketable Strike	Marketable Rushmore
1994	40.1	63.0**	21.4	33.2*
1995	21.0	33.7**	8.6	12.9**

*,**Indicates significant difference between sheltered and exposed at $P \leq 0.1$ and 0.05, respectively.

Table 7. Gross wholesale market value for snap beans marketable yield ($/ha) from areas sheltered and exposed to wind over seven harvest dates in 1994 and five harvest dates in 1995.

1994					1995				
Planting dates	Harvesting dates	Price per bu[z]	Yield ($/ha) Sheltered	Exposed	Planting dates	Harvesting dates	Price per bu[z]	Yield ($/ha) Sheltered	Exposed
25 Apr.	4 July	14.00	3368	1469	18 May	17 July	15.50	5867	2477
9 May	8 July	22.00	7735	6678	30 May	7 Aug.	16.00	7293	3010
23 May	18 July	17.00	8299	5692	13 June	10 Aug.	14.00	4514	3171
10 June	4 Aug.	11.00	7037	3808	27 June	9 Sept.	20.00	11849	8785
5 July	28 Aug.	14.00	8939	7685	11 July	23 Sept.	10.00	4012	3182
19 July	24 Sept.	10.00	1824	1421					
2 Aug.	16 Oct.	14.00	5500	2386					
Season average		14.57	6100	4163			15.10	6707	4125

[z]Prices were based on Chicago Wholesale Market Report; 1 bushel (bu) = 30 lb = 13.62 kg.

greatest of these is the land planted to the shelterbelt and the lost production associated with these areas. Brandle et al. (1992) have demonstrated that a crop field can be totally protected by diverting between 5% and 8% of the land base to shelterbelts. If we adjust our economic values to accommodate an 8% land diversion, sheltered areas returned $5,612/ha in 1994 and $6,170 in 1995. On average for the 2-year study, shelterbelts contributed to a 42% increase in gross return to the producer. The magnitude of yield differences between a production-sized snap bean crop protected by tree windbreaks and yields from a comparable unprotected snapbean crop may differ from this research.

For each harvest, a higher marketable yield and, therefore, potential gross return was obtained from the sheltered bean crop. In 1995, despite the unusually dry weather conditions throughout the growing season, snap bean producers still could have expected significant economic benefit from providing wind protection. The values suggest that despite relatively lower marketable pod yields early and late in the season, higher gross return could still be obtained from sheltered bean crops due to higher seasonal prices plus the increased production in the sheltered areas.

The generally favorable response to wind reduction on the growth and yield of many crops has been documented (Bagley and Gowen, 1960; Frank et al., 1974; Ogbuehi and Brandle, 1982; Radke and Burrows, 1970; Rosenberg et al., 1966; Skidmore et al., 1974; Sturrock, 1975, 1981). The results obtained in this study support the general pattern except that yields (total and marketable) and greater early- and late-season yields are found to be important factors. This is also the first time detailed hourly averages for microclimate changes due to wind protection have been documented in association with snap bean production. Wind protection of snap beans resulted in a substantial increase in the calculated gross market value due to a higher proportion of marketable beans obtained from the sheltered areas. This improvement in the weight of marketable beans was associated with the more advanced crop maturity in wind sheltered areas. Although the financial advantages presented in this study were extrapolated based on the harvest from small plots in the zone of maximum wind protection, such information is useful for both growers and processors in managing snap bean production.

Conclusions

Microclimate was altered by the presence of windbreaks in the snap bean field. Changes in wind speed create changes in microclimatic elements which in turn affect the growing plants. Snap beans sheltered by windbreaks had greater total internode lengths, produced significantly more dry weight, and had a greater leaf area index than snap beans exposed to wind. Higher daytime air temperatures and higher soil temperatures as a result of lower wind velocities and less total exposure time to winds under sheltered conditions appear to have promoted this rapid vegetative growth and earlier maturity.

The year-to-year variability of shelter effects on snap bean yields in this study was due to differences in weather conditions between the two study years. This study supports the suggestion that shelterbelts are of greatest benefit during dry years. In 1994, wind protection increased total and marketable snapbean pod yields 47% and 50% compared to 64% and 92%, respectively, in 1995, the drier year. More studies under controlled moisture conditions are needed to determine how moisture availability affects shelter-induced crop yield increases. The increases were due primarily to more rapid rates of plant development as a result of generally improved growing conditions in sheltered areas. During both study years, 'Rushmore' produced significantly greater total and marketable pod yields than 'Strike'. There was no significant interaction of shelter × planting date or planting date × cultivar for the total and marketable yield in either 1994 or 1995.

Snap bean growth and yield were significantly affected by planting date in both study years. Crops planted during midseason tended to be more vigorous than the crops planted earlier or later in the season and produced more total and marketable snapbeans except when heat and soil moisture stress resulted in flower abortion and pod abscission.

Crop value estimates based on extrapolated marketable yield showed substantial increase in the calculated gross market value of beans when produced with wind protection provided by shelterbelts due to both a higher total yield and a higher proportion of marketable beans from these sites. Gross wholesale value increased 47% and 63% in sheltered areas in 1994 and 1995, respectively. Values on the financial advantages obtained from this analysis are slightly inflated as yield samples were hand harvested from the crops grown in an area that received maximum wind protection from tree windbreaks. This emphasizes the necessity of conducting similar shelter studies at various degrees of protection over a number of years. Such information would allow growers and processors to consider the effects of wind-sheltered microclimate in scheduling planting and harvest of crops.

Literature Cited

Bagley, W.T. 1964. Response of tomatoes and beans to windbreak shelter. J. Soil and Water Conservation 19:71–73.

Bagley, W.T. and A.F. Gowen. 1960. Growth and fruiting of tomatoes and snap beans in the shelter area of windbreak. Proc. 5th World For. Congr. 3:1667–1671.

Baldwin, C.S. 1988. The influence of field windbreaks on vegetable and specialty crops. Agr. Ecosystems and Environ. 22/23:191–203.

Barker, G.L., J.L. Hatfield, and D.F. Wanjura. 1985. Cotton plant response to wind and water stress. Trans. Amer. Soc. Agr. Eng. 28:194–100.

Borst, H.L. and L.E. Thatcher. 1987. Life history and composition of soybean plants. Ohio Agr. Expt. Sta. Bul.

Brandle, J.R., B.B Johnson, and T. Akeson. 1992. Field windbreaks: Are they economical? J. Prod. Agr. 5:393–398.

Brandle, J.R., L. Hodges, and J. Stuthman. 1994. Windbreaks and specialty crops for greater profits. Proc. Agrofor. and Sustainable Systems Symp. Fort Collins, Colo. p. 81–91.

Deakin, J.R. 1973. Association of seed color with emergence and seed yield of snap beans. J. Amer. Soc. Hort. Sci. 99:110–114.

Denmead, O.T. and R.H. Shaw. 1959. The effects of soil moisture stress at different stages of growth and development and yield of corn. Agron. J. 52:272–275.

Dickson, M.H. 1971. Breeding beans *Phaseolus vulgaris* L. improved germination under unfavorable temperature condition. Crop Sci. 11:848–850.

Dickson, M.H. and M.D. Boettger. 1984. Effect of high and low temperatures on pollen germination and seed set in snap bean (cold tolerance). J. Amer. Soc. Hort. Sci. 109:372–374.

Felch, R.E. 1964. Growth and phenological responses of irrigated dry beans to changes in microclimate induced by a wind barrier. MS thesis. Univ. Nebraska–Lincoln.

Finch, S.J. 1988. Field windbreaks: Design criteria. Agr. Ecosystem and Environ. 22/23:215–228.

Frank, A.B., D.G. Harris, and W.O. Willis. 1974.

Windbreak influence on water relations, growth, and yield of soybeans. Crop Sci. 14:761–765.

Frank, A.B. and W.O. Willis. 1978. Effect of winter and summer windbreaks on soil water gain and spring wheat yield. Soil Sci. Soc. Amer. J. 42: 950–953.

Gepts, P. 1987. Characterizing plant phenology: Growth and development scales, p. 3–24. In: J.D. Hesketh and K. Wisiol (eds.). Plant growth modeling for resource management. Vol. 2. Academic Press, New York.

Kigel, J., I. Konsens, and M. Ofir. 1991. Breeding, flowering and pod-set patterns on snap bean (*Phaseolus vulgaris* L.) as affected by temperature. Can. J. Plant. Sci. 71:1233–1242.

Konsens, I., M. Ofir, and J. Kigel. 1991. The effect of temperature on the production and flowers and pods in snap bean (*Phaseolus vulgaris* L.) Ann. Bot. 67:391–399.

Lin, T.Y. and A.H. Markhart. 1996. *Phaseolus acutifolius* A. Gray is more heat tolerant than *P. vulgaris* L. in absence of water stress. Crop Sci. 36:110–120.

Marx, G.A., W.T. Schroeder, R. Provvidenti, and W. Mist. 1972. A genetic study of tolerance in pea (*Pisum sativum* L.) aphanomyces root rot. J. Amer. Soc. Hort. Sci. 97:619–621.

Mitchell, C.A. and P. N. Myers 1995. Mechanical stress regulation of plant growth and development. Hort. Rev. 17:1–42.

Monterroso, V.A. and H.C. Wien. 1990. Flower and production abscission due to heat stress in beans. J. Amer. Soc. Hort. Sci. 115(4)631–634.

Neild, R.E. and J.K. Greig. 1972. An agroclimatic procedure to determine growing seasons for vegetables. Agr. Meteorol. 14:321–333.

Ogbuehi, S.N. and J.R. Brandle. 1982. Influence of windbreak-shelter on soybean growth, canopy structure, and light relations. Crop Sci. 22:269–273.

Radke, K. and W. Burrows. 1970. Soybean plant response to temporary field windbreaks. Agron. J. 62:424–429.

Rosenberg, N.J. 1966. Microclimate, air mixing and physiological regulation of transpiration as influenced by wind shelter in an irrigated bean field. Agr. Meteorol. 3:197–224.

Rosenberg, N.J. 1967. The influence and implications of windbreaks on agriculture in dry regions. In: R.H. Shaw (ed.). Ground level climatology. Amer. Assn. Adv. Sci.

Rosenberg, N.J. B.L. Blad, and S.B. Verma. 1983. Microclimate: The biological environment. Wiley, New York.

SAS Institute, Inc. 1985. SAS user's guide: Statistics, Vers. 5 ed. SAS Inst., Cary, N.C.

Shah, S.R.H. 1962. Studies on wind protection. Commun. No. 6. Instituut voor Toegepast Bilogisch Onderzoek in de Natuut, Arnhem. Cited in Kort, John, 1988. Benefits of windbreaks to field and forage crops. Agr. Ecosystems Environ. 22/23:165–190.

Skidmore, E.L., L.J. Hagen, D.G. Nayalor, and I.D. Teare. 1974. Winter wheat response to barrier-induced microclimate. Agron. J. 66:501–505.

Sturrock, J.W. 1975. The control of wind in crop production. Progress in biometeorology, p. 349–368. In: L.P. Smith (ed.). The effects of weather and climate on plants. Swets and Zeitlinger, Amsterdam.

Sturrock, J.W. 1981. Shelter boosts crop yield by 35 percent: Also prevents lodging. N.Z. J. Agr. 143:18–19.

USDA–ARS Fruit and Vegetable Division. 1994, 1995. Fruit and vegetable market news–Chicago. vol. 80, 81. USDA–ARS, Chicago.

van Eimern, J., R. Karschon, L.A. Razumova, and G.W. Robertson. 1964. Windbreaks and shelterbelts. WMO Technol. Note 59.