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 (Netid 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 were reclassified in the Aksarben series). 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 m² in 1994 and 1115 m² 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 meteorological 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 snapbean 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
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), R3 (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 fill) based on (Gepts, 1987). In 1994, samples for growth and development measurements were taken at the first three developmental stages as in 1995 plus at the R7 (pod wall fill) based on (Gepts, 1987). In 1995, samples for growth and development measurements were taken at the first three developmental stages as in 1995 plus at the R7 (pod wall fill) based on (Gepts, 1987).

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 ** 73.84 72.16 **  
- 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  

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. | Sheltered 1994 | Exposed 1994 | Sheltered 1995 | Exposed 1995 |
|----------------------|--------------|----------------|---------------|----------------|---------------|
| 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 | 24.74 *** |
| | 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 ** | 73.84 | 72.16 ** |
| | 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 | | |

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 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 m 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).
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
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 GDD15 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 GDD15 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 GDD15 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 ≤ 0.05). It appears these interactions were related to significantly higher soil temperatures in the sheltered areas during these periods (P ≤ 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 $P = 0.05$. 

**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 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 in either sheltered or exposed areas \((r = 0.34, P > 0.05; \text{and } r = 0.14, P > 0.05, \text{respectively})\). In the following year, there was a positive correlation between the percent emergence and soil GDD 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 van Eimern 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 in either sheltered or exposed areas \((r = 0.34, P > 0.05; \text{and } r = 0.14, P > 0.05, \text{respectively})\). 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 \((P < 0.05; r = 0.31 \text{ and } 0.77, \text{respectively})\). Dickson (1971) reported greater tolerance to Pythium root rot 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 \((r = 0.77, P = 0.07)\) associated with less wind, including less plant movement \((r = 0.97, P < 0.05; \text{and } r = 0.77, P = 0.07)\). Regression analysis between the accumulated air GDD and internode lengths for the June 10 planting in 1994 gave a correlation coefficient \((r) = 0.97\). In 1995, the r values for air GDD 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 \((r = 0.77, P = 0.05)\). Plant height increases induced by windbreaks have been reported for snap beans \((Bagley and Gowen, 1960; Rosenberg et al., 1967), dry beans \((Felch, 1964), \text{as well as soybeans} \(Ogbuehi and Brandle, 1982; \text{Radlke and Burrow, 1970}), \text{wheat} \(Frank and Willis, 1978; \text{Skidmore et al., 1974}), \text{oats} \(Sturrock, 1981), \text{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 3. Seasonal summaries of air and soil growing degree-days (GDD) in areas sheltered and exposed to wind during the 1994 and 1995 growing seasons.**

| Year | Planting Date | Days to Harvest | Air GDD<sub>15</sub> | Soil GDD<sub>15</sub> | Sheltered | Exposed | Sheltered | Exposed |
|------|---------------|----------------|----------------------|----------------------|-----------|---------|-----------|---------|
| 1994 | 25 Apr.       | 73             | 392, 375             | 607<sup>**</sup>, 448 | 637<sup>**</sup>, 483 |         |         |         |
|      | 9 May         | 62             | 411, 398             |                      | 662<sup>**</sup>, 541 |         |         |         |
|      | 23 May        | 58             | 427, 412             | 819<sup>**</sup>, 699 | 650<sup>**</sup>, 545 |         |         |         |
|      | 7 July        | 51             | 347, 338             |                      | 814<sup>**</sup>, 635 |         |         |         |
|      | 19 July       | 69             | 410, 400             | 661<sup>**</sup>, 482 | 900<sup>**</sup>, 790 |         |         |         |
|      | 8 Aug         | 76             | 342, 337             |                      | 863<sup>**</sup>, 766 |         |         |         |
|      | Full season   | 175            | 934, 907             |                      | 1092<sup>**</sup>, 946 |         |         |         |
| 1995 | 18 May        | 61             | 346, 344             | 631<sup>*</sup>, 524 | 900<sup>**</sup>, 790 |         |         |         |
|      | 30 May        | 69             | 547, 569             |                      | 1049<sup>**</sup>, 900 |         |         |         |
|      | 13 June       | 59             | 553, 546             |                      | 836<sup>**</sup>, 766 |         |         |         |
|      | 27 June       | 75             | 710, 699             | 1092<sup>**</sup>, 946 | 900<sup>**</sup>, 790 |         |         |         |
|      | 11 July       | 75             | 661, 649             | 1049<sup>**</sup>, 900 | 900<sup>**</sup>, 790 |         |         |         |
|      | 25 July<sup>5</sup> | 60       | 487, 476             | 799<sup>**</sup>, 669 | 900<sup>**</sup>, 790 |         |         |         |
|      | Full season   | 128            | 907, 891             | 1554<sup>**</sup>, 1309 | 900<sup>**</sup>, 790 |         |         |         |

<sup>1</sup>Average soil temperature for the 7 d after planting.
<sup>2</sup>Significant at \(P = 0.01\), or 0.05.
<sup>3</sup>Significant at \(P = 0.05\).
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 planting dates. Total yields from sheltered and exposed snap beans (average of two cultivars) at each sampling stage.

| Planting date | SS* | DAP* | Sheltered | Exposed | Sheltered | Exposed | Sheltered | Exposed |
|---------------|-----|------|-----------|---------|-----------|---------|-----------|---------|
| 1994          |     |      |           |         |           |         |           |         |
| 10 June V3    | 15  | 6.11 | 24.86     | 27.35   | 0.23      | 0.24    |           |         |
| V5            | 35  | 9.62 | 208.13    | 56.80   | 3.35      | 2.51    |           |         |
| R7            | 47  | 22.11| 240.56    | 170.04  | 0.52      | 11.10   |           |         |
| R8            | 55  | 60.49| 1394.96   | 1040.04 | 3.08      | 10.52   |           |         |
| 1995          |     |      |           |         |           |         |           |         |
| 18 May V3     | 27  | 3.67 | 86.83     | 42.75   | 0.58      | 0.34    |           |         |
| V4            | 32  | 6.68 | 266.87    | 152.76  | 1.64      | 1.04    |           |         |
| R5            | 43  | 22.19| 703.08    | 453.18  | 4.98      | 3.44    |           |         |
| R7            | 57  | 68.51| 1643.31   | 1003.58 | 15.86     | 10.10   |           |         |
| R8            | 61  | 79.10| 1313.07   | 1063.78 | 5.03      | 11.67   |           |         |
| 13 June V3    | 17  | 4.41 | 81.77     | 79.82   | 0.47      | 0.52    |           |         |
| V4            | 23  | 5.77 | 256.75    | 230.59  | 1.53      | 1.56    |           |         |
| R5            | 37  | 45.01| 1039.35   | 409.25  | 10.56     | 10.10   |           |         |
| R7            | 48  | 67.65| 1854.32   | 1448.14 | 12.79     | 11.28   |           |         |
| R8            | 59  | 102.27| 2653.37  | 2057.72 | 25.10*** | 20.61   |           |         |
| 11 July V3    | 29  | 3.41 | 91.71     | 90.03   | 0.55      | 0.71    |           |         |
| V4            | 38  | 19.30| 256.86    | 367.80  | 1.79      | 1.82    |           |         |
| R5            | 52  | 30.10| 1014.96   | 588.56  | 6.08      | 3.80    |           |         |
| R7            | 67  | 42.44| 1056.02   | 949.28  | 10.66     | 10.03   |           |         |
| R8            | 75  | (na) | (na)      | (na)    | 25.00     | 34.50   |           |         |

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

Days after planting.

Indicates sheltered is significantly different from exposed at P ≤ 0.1, 0.05, and 0.01, respectively.

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 | Total | Marketable |
|------|-------|------------|
|      | Sheltered | Exposed | Sheltered | Exposed | Sheltered | Exposed |
| 1994 | 61.3 | 41.8 | 12.5 | 21.9 | 14.2 | 7.4 |
| 1995 | 33.9 | 20.7 | 12.5 | 21.9 | 14.2 | 7.4 |

Avg yield (g/plant) of two cultivars and all planting dates

## 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 $1,406/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 average aged $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
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; Ogibuei and Brandle, 1992; 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.

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