RESPONSE OF SOYBEANS (GLYCINE MAX L.) TO ANNUAL CROP WINDBREAKS IN MANITOBA

A Thesis
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Arumugam Senthinathan

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ABSTRACT

Senthinathan, Arumugam. M.Sc., The University of Manitoba, May, 1983.

Response of Soybeans (Glycine max L.) to Annual Crop Windbreaks in Manitoba.

Major Professor; Dr. E.H. Stobbe.

Phenological development, vegetative growth, and yield responses of soybeans (Glycine max L. cv. McCall) to parallel sunflower (Helianthus annuus L. cv. Hybrid Cargill - 204) windbreaks of differing permeabilities were studied over a two year period. Permeability of the windbreaks was varied by planting one or two rows of sunflowers.

The results of the study indicated that the windbreaks did not beneficially influence the rate of phenological development or measured vegetative growth parameters such as plant height, leaf area and top dry weight in either year. Additionally yield related parameters such as number of pods per plant, seed weight, seed quality and seed yield were not beneficially influenced by windbreaks in 1982.

However, in 1981, the two row sunflower windbreak treatment produced a statistically significant reduction in number of pods per plant and seed yield as well as a statistically significant increase in the weight and oil content of seeds. These statistically significant effects were thought to be due to stress conditions on the soybeans induced by the low permeability of the two row sunflower windbreak treatment in 1981.

Except as noted above, the differences in permeability between the one and two row sunflower treatments did not result in statistically significant differences in phenological development, measured vegetative parameters or yield parameters.

Windbreaks influenced both the canopy air and air temperatures. Canopy air temperature differences seemed to indicate moisture stress and also seemed to be responsible for differences in seed weight and quality.

Windbreaks did not influence the total water use of soybeans.

INTRODUCTION

Manitoba uses about 60% of all soybeans imported into western Canada. Growing of soybeans as a viable oil-protein seed crop in this province is limited because of a short growing season, long summer day lengths, and below optimum soil and air temperatures during the spring (Stefannson 1967). However, the recent development of new early maturing soybean varieties has improved the potential of growing soybeans in southern Manitoba. Even so, the low soil and air temperatures during early spring may delay the emergence and development of soybeans.

Soil manipulation and windbreaks are used in many countries to modify the soil and ambient environments favourably for increased growth, development, and yield of soybeans and other crops. Both annual and perennial windbreaks are used to modify the microclimate of ambient environments.

Increased soil and air temperatures and reduced potential evapotranspiration are the major microclimatic parameters modified by the windbreaks (Van Eimern et al. 1964, Marshall 1967). Thus in Manitoba the increased soil and air temperatures and reduced potential evapotranspiration due to windbreaks may enhance the growth and development of soybeans, especially during spring when both the soil and air temperatures are well below the optimum level.

In 1981 and 1982, a study was undertaken to assess the effects of annual windbreaks on ambient temperature and soybean water use under Manitoba climatic conditions and to determine the vegetative and reproductive responses of soybeans to annual crop windbreaks of different permeabilities.

LITERATURE REVIEW

Climate of Southern Manitoba

Agriculture in Manitoba is determined by the date of occurrence of the late spring and early autumn frosts, number of frost-free days available for crop growth, precipitation from May 1 to September 30, and soil moisture status during critical stages of crop growth (Dunlop and Shaykewich 1982). The frost-free period available for crop production, together with a knowledge of the climatic requirements of crops, determine what crops can be grown successfully in a given region of the province.

Dunlop and Shaykewich (1982), based on their calculations of 50, 25, and 10% probabilities of occurrence of late spring and early autumn frosts and number of frost-free days, indicated the region between the Manitoba Escarpment and the Red River Valley has the greatest potential for agriculture. It has an average frost-free period of more than 120 days and 145 days or more above -2.2° C. The Red River Valley is second in potential in agriculture with a frost-free period of about 120 days. The areas to the west of the Escarpment have a frost-free period of approximately 105 to 110 days. It should be noted that the frost-free period is only relevant to crops if conditions during the frost-free period approach those of their crop requirements.

Even in areas with adequate frost-free periods, the early spring and late autumn temperatures are marginal for the growth and maturity of many crop species. This led to the development of the degree-day and the corn heat unit concepts to classify the agricultural areas into different regions and to establish crop suitability for these different regions. The average degree days above 5° C in the period of May 1 to September 30 shows a maximum accumulation of 1700 units in the Morden-Morris area and a minimum of 1400 units in the Riding Mountain and Bristol-Russel area (Dunlop and Shaykewich 1982). Similarly, accumulation of average corn heat units vary from 2500 units in the area south of Lake Manitoba between the Manitoba Escarpment and the eastern edge of the Red River Valley to 2200 units or less west of the Manitoba Escarpment and north of the Assiniboine River (Dunlop and Shaykewich 1982).

The day length also determines the suitability of crop species and crop varieties within a species for a particular region. The day length during the growing season varies and reaches a maximum of 16½ hr during the summer solstice. The day length is fairly constant throughout southern Manitoba.

Long day winter cereals such as wheat, barley, rye, and oats are best adapted to this area. Short day crops such as soybeans fail to flower early enough to escape frost damage because of long days. However, cultivars of soybeans belonging to 00 and 0 groups are adapted to a long photoperiod and thus are adapted to southern Manitoba.

Spring-stored soil moisture, together with precipitation from May 1 to September 30, gives the total amount of water available for crop production. Most of Manitoba receives about 325 mm of precipitation during the growing season and shows little seasonal and locational variation (Dunlop and Shaykewich 1982). The wettest area is the southeast corner of the province, while the driest areas are in the west and southwest regions.

The Influence of Windbreaks on Microclimatic Parameters

We cannot modify macroclimatic parameters outlined above to any great extent, with the exception of water by using irrigation. However, the microclimatic parameters in the immediate vicinity of a plant or plant community can be modified by several means including windbreaks.

Windbreaks change the ambient air-flow, and thus by modifying the aerial environment, have the potential to affect crop growth and yield. Characteristics of both windbreaks and incident wind determine leeward air-flow, and thus the sheltered area characteristics.

Barrier Modified Air-Flow: Windbreak Characteristics

Windbreak characteristics that affect leeward air-flow include height, permeability, length, width, and shape (Skidmore 1969). These characteristics are all inter-related.

Height. The extent to which shelter is provided is proportional to the windbreak height. The higher the windbreak, the greater the distance of its downward and upward influence. Sheltered distances are generally expressed as multiples of effective heights (H) (Van Eimern et al. 1964).

Permeability. Permeability (density or porosity) is the next most important characteristic that determines the extent of the sheltered zone. At low windbreak porosities, leeward air-flow patterns are characterized by minimum leeward wind speed occurring closer to the windbreak and a tendency to increase more quickly after reaching a minimum than do wind speeds leeward of more porous windbreaks (Woodruff et al. 1963, Van Eimern et al. 1964, Marshall 1967, Skidmore and Hagen 1970a, Plate 1971, Skidmore et al. 1972). Very dense barriers stimulate turbulence (Van Eimern et al. 1964, Skidmore and Hagen 1970a, Skidmore et al. 1972, Radke and Hagstrom 1974). At higher windbreak permeabilities, turbulence becomes negligible but so does the degree of shelter provided (Caborn 1957). Skidmore and Hagen (1970a), in a wind tunnel study with model windbreaks of porosities 60, 40, 20, and 0%, found a 40% porous barrier reduced wind speed most over the 0 to 30 H interval.

Permeability of living barriers are difficult to estimate and are determined by the plant species, their growth habit, and the number of rows in the planting. The optimum permeability depends somewhat on the purpose of the wind barrier. Optimum protection for vegetation is provided by a barrier with a geometric permeability of 40 to 50% with small holes evenly distributed (Jensen 1954, Caborn 1957, George et al. 1963, Woodruff et al. 1963, Van Eimern et al. 1964). Read (1964) indicated a density of 80% was best for corn in Nebraska and South Dakota. Ideally, the porosity of the barrier should decrease with height in proportion to the logarithmic nature of the wind speed profile (Rosenberg 1975).

Length. The length of a windbreak is important in maintaining a reasonable degree of shelter when wind veers from a direction perpendicular to the barrier. Woodruff and Zingg (1952) found in their wind tunnel studies that the area protected up to 20 H is proportional to the square of the length of the barrier perpendicular to the wind. Beyond this limit the area appeared to be directly proportional to length.

Shape and width. Woodruff and Zingg (1952) used different solid geometrical shapes and tree models, and showed that tree models achieved a 25% or more wind speed reduction compared to solid geometrical models, which reduced wind speed more than 50%. They attributed this difference in wind reduction to permeability and shape of the wind barriers. Woodruff and Zingg (1953) modelled various shapes with tree models and found an inverted 'V' shape model gave the greatest extent of wind speed reduction.

Van Eimern et al. (1964), in their review, reported studies with different shapes of windbreaks for different purposes.

Barrier Modified Air-Flow: Wind Characteristics

Shelter effects in a given wind barrier protected field is also known to be a function of wind characteristics. These characteristics include speed, direction (angle of incident wind), thermal stability, and turbulence level (Skidmore 1969).

Wind speed.

The main purpose of a windbreak is to reduce the surface wind speed to some favourable level in the sheltered zone. Leeward wind reducing patterns were similar irrespective of the level of unobstructed velocity at relatively high Reynolds numbers (Woodruff and Zingg 1952, Moysey and McPherson 1966). But Woodruff and Zingg (1952) reported that absolute protection was, however, dependent on the level of unobstructed wind. Van Eimern et al. (1964) cited the theoretical investigations of Kaiser (1959) for justification of the use of relative values to compare wind reducing effects of windbreaks. They also noted that the effective porosity of a barrier changed with change in wind speed and hence, the area sheltered.

Wind direction.

The greatest effects from windbreaks are achieved when wind blows perpendicular to the windbreak. When wind blew at an angle less than 90 degrees, the protected zone dwindled for obvious geometrical reasons as well as because of changes in permeability of the barrier (Van Eimern et al. 1964). Even when wind blew parallel to the barrier, a sheltered zone up to 5 H distance beside wind barriers was achieved because of inevitable variation in wind direction and the friction at and above the wind barrier (Van Eimern _et al_. 1964). Whenever wind direction was indeterminate, shelter was best provided by a network of wind barrier systems (Marshall 1967).

Thermal stability. The degree of sheltering provided by a barrier varied somewhat with the stability of the atmosphere (Staple and Lehane 1955). When all other factors were equal, with unstable temperature conditions, minimum wind speed occurred closer to the barrier and extended a shorter distance. Whereas under stable temperature gradient conditions, the wind was reduced to a greater distance, because more force was required by the stable air mass to flow over the barrier, so the amount of flow penetrating the barrier increased with increasing wind speed (Van Eimern _et al_. 1964).

Turbulence. The roughness of the ground surface and the presence of other barriers affect the turbulence of approaching wind. Jensen (1954) used model screens placed in a wind tunnel with varying degrees of surface roughness, and showed that the wind was reduced to a lesser distance on a rough surface than on a smooth surface. The point of greatest wind reduction was closer to the barriers with rough surfaces than it was to barriers with smooth surfaces. Thus different degrees of roughness caused a stretching or compression of leeward wind distribution patterns.

Woodruff and Zingg (1955) showed in their wind tunnel and atmospheric air-flow studies that three or four successive barriers were not enough to create a beneficial accumulative surface effect on air flow. George (1960) and Staple and Lehane (1955) also showed no accumulative effect behind staggered belts. Woodruff and Zingg (1955) suggested from their results that a spacing of about 10 H should give better overall protection than the 15 H they used in their experiment. Staple and Lehane (1955) concluded that an interval of 20 H between parallel windbreaks was favourable in North America.

Nageli (1965), in Skidmore and Hagen (1970b), indicated the lack of accumulative shelter effect due to a series of windbreaks was due to increased air turbulence.

Sheltered Zone

The extent of the sheltered zone varies with changes in the characteristics of windbreaks and incident wind. The sheltered zone varied between 1 and 10 H on the windward side and 8 to 60 H on the leeward side of the barrier according to a review by Van Eimern *et al*. (1964). A 20% wind reduction is accepted by many workers as the optimum level for producing favourable microclimate. It was achieved for distances up to 20 H leeward and 2 H windward with a 40 to 50% porous barrier (Van Eimern *et al*. 1964, Marshall 1967, Rosenberg 1975). The sheltered area was parabolic in shape, regardless of the angle incident wind (Woodruff and Zingg 1952).

The extent of shelter provided by temporary or annual windbreaks was somewhat different than that of perennial windbreaks (Radke and Burrows 1970). Temporary or annual windbreaks compared to perennial windbreaks did not provide a larger area of year round protection, but they provided almost immediate protection for a smaller area (Brown and Rosenberg 1975). Several workers used small temporary crop barriers in their experiments (Bagley 1964, Brown and Rosenberg 1970, 1971, 1972, Radke and Hagstrom 1973) or constructed barriers (Rosenberg 1966a, Pelton 1967, Rosenberg *et al*. 1967, Skidmore and Hagen 1970a, Sturrock 1970a, Frank and Willis 1972, Skidmore *et al*. 1972, Miller *et al*. 1973, Frank *et al*. 1974, Skidmore *et al*. 1975, Frank *et al*. 1977a, 1977b) or combination of both (Rosenberg 1966b, Radke and Burrows 1970, Radke and Hagstrom 1974) to provide shelter for different crop species.

The results of the above cited experiments indicated that the modified microclimate improved growth and yield of crop species tested, even though the area of the sheltered zone was smaller for annual than for perennial shelterbelts.

Effects of Barrier Modified Air-Flow on Micrometeorological Parameters

Turbulent exchange coefficient. The turbulent exchange coefficient is a function of wind speed and temperature gradient. Windbreaks, by reducing wind speed, modify the turbulent exchange in the sheltered zone. Wind shear measurements by Rosenberg (1966b) indicated that a reduction of turbulent exchange occurred in sheltered areas. Brown and Rosenberg (1971) calculated turbulent exchange coefficients in a sugar beet field sheltered by corn windbreaks by means of an energy balance and found exchange coefficients were 25% lower, on average, in the sheltered areas. Miller et al. (1973) used a precision weighing lysimeter to determine soybean water use and flux rates of water vapour transfer, and showed a 10 to 25% reduction in turbulent exchange coefficients. Van Eimern et al. (1964) and Brown and Rosenberg (1971) also reported many Russian experiments, which showed reduction in turbulent exchange in sheltered areas. This reduction of turbulent exchange provides a better explanation of the unique microclimate and plant growth in shelter than does the reduction in wind speed (Rosenberg 1975).

Radiation. Barrier-modified air-flow has no effect on radiation balance in the sheltered areas. However, radiation was slightly affected by windbreaks, especially in the immediate vicinity of the windbreaks (Van Eimern et al. 1964, Rosenberg 1966a, Marshall 1967, Rosenberg 1967). Rosenberg (1967) suggested that long shadows are cast only when the sun is low and solar radiation is low, hence the effect may be unimportant. Marshall (1967) reported on many investigations which indicated that the effect of shading is probably unimportant beyond 1 to 2 H around 50° N latitude irrespective of the orientation of the windbreak. Rosenberg (1966b) observed that a slat barrier in a sugar beet field did not affect either daytime or nighttime radiation.

Air and soil temperature. A number of investigations showed higher daytime and lower nighttime air temperatures in the sheltered areas, compared to unsheltered areas as a result of a reduced turbulent transfer coefficient (Van Eimern et al. 1964, Rosenberg 1966a, 1966b, Marshall 1967, Rosenberg et al. 1967, Skidmore and Hagen 1970a, Brown and Rosenberg 1972, Skidmore et al. 1972, Radke and Hagstrom 1973, Maki 1980). However, Woodruff et al. (1959) observed both higher and lower daytime air temperatures leeward of a barrier. They related the leeward air temperature patterns to the eddy zones produced within the sheltered areas. Hagen and Skidmore (1971) also observed that higher and lower daytime temperatures, compared to open field temperatures, occurred in positions where the mean component of air-flow was upward and downward, respectively. Higher daytime or lower nighttime temperatures occurred leeward in the area of lowest wind speed, which varied with the porosity of the barrier (Skidmore and Hagen 1970a). Maki (1980) also observed daytime maximum surface water and leaf temperatures over a paddy rice field occurred in the area of lowest wind speed in the sheltered zone. Skidmore and Hagen (1970a) found the ambient air temperature at 2 H leeward of 60, 40, and 0% porous barriers was higher by 0.9, 1.2, and 1.5° C, respectively, compared to the temperature at 6 H windward.

Brown and Rosenberg (1972) reported that the difference in temperature between sheltered and open field were greater during midday. Temperature differed more in the afternoon than in the morning. They also observed that differences in air temperatures decreased with increasing wind speed. Maki (1980) reported that warming effects on clear days were larger than on cloudy days.

Guyot (1963) cited by Rosenberg (1967) stated that the effects of shelter on air temperature may be predicted based on whether evaporation is increased or decreased.

When turbulent exchange was restricted or reduced, the aerodynamic resistance increased and temperature gradients were intensified (Woodruff _et al_. 1959, Van Eimern _et al_. 1964, Rosenberg 1966a, 1966b, Marshall 1967, Skidmore _et al_. 1972, Miller _et al_. 1973). This greater amplitude in the difference of higher daytime and lower nighttime temperatures may have physiological significance to the growth of the sheltered plants.

As the barrier modifies leeward airflow, heat transfer to and from soil is also altered. Jensen (1954) in Denmark and European workers (Van Eimern _et al_. 1964) have consistently noted increased soil temperature in the sheltered zone. They also reported a proportional increase in soil temperature with increases in wind protection. Rosenberg (1966b) found soil temperatures under irrigation in a sugar beet plot sheltered by snow-fence were 1 to 2° C higher by day and a fraction of a degree lower by night, with higher average temperatures compared to unsheltered plots. Van Eimern _et al_. (1964) and Marshall (1967), in their reviews, indicated that the greatest temperature differences occurred when the soil was dry and bare, and the lowest temperature differences occurred when the soil surface was moist and the sky was cloudy.

Air humidity and water vapour pressure. Several factors, like soil moisture, evaporation and transpiration, diffusion, and air mixing as well as temperature and radiation influence the air humidity and water vapour pressure.

A wind barrier, in turn, influences these factors and complicates the conditions (Van Eimern _et al_. 1964). Many studies showed only slight variations of relative humidity and water vapour pressure in sheltered zones compared to unsheltered zones (Van Eimern _et al_. 1964, Marshall 1967).

Rosenberg (1966a) noted higher absolute humidity and vapour pressure (2 to 3 mb) in bean plots sheltered by square snow-fence compared to unsheltered areas. But, parallel snow-fence or corn windbreaks had little influence on atmospheric humidity or water vapour pressure in the sheltered area of sugar beets (Rosenberg 1966b).

Skidmore and Hagen (1970a) found that absolute humidity was slightly higher 2 H leeward than in the open. The differences were 1.5, 3.1, and 2.6 mb, respectively, for 60, 40, and 0% porous barriers. At 12 H leeward, the vapour pressure was less than windward by 0.7, 2.0, and 2.5 mb, respectively, for 60, 40, and 0% porous barriers.

Evapotranspiration (potential and actual). Windbreaks influence evapotranspiration through modification of the air humidity and wind dominant terms of evapotranspiration.

Potential evapotranspiration is a function of energy input and wind or turbulent transport (Van Bavel _et al_. 1967). The energy input term is derived from solar radiation and is unaffected by wind. However, wind along with temperature and water vapour pressure gradients causes transfer of sensible heat and water vapour, which results in evaporation.

Skidmore _et al_. (1969) studied evapotranspiration on two representative and consecutive non-windy and windy days in Kansas and found that the wind dominant term contributed 33 and 113%, respectively, as much as the radiant dominant term to total calculated potential evapotranspiration. Nageli, as quoted in a review by Van Eimern _et al_. (1964), compared evaporation from moist clay containers and found an excellent relation of evaporation potential to the square root of wind speed.

Shelter causes both increased air temperature and air humidity. Increased air temperature increases the evaporative demand, while the increased air humidity decreases the evaporative demand. These two processes tend to offset each other in changing evaporative demand (Skidmore and Hagen 1970a).

Windbreaks reduce wind speed and consequently reduce potential evaporation. Many studies suggested that this effect is the main benefit derived from windbreaks (Van Eimern _et_ _al_. 1964, Staple 1961, Davenport and Hudson 1967).

In shelter studies, potential evaporation was measured using atmometers, evaporation pans, and wetted soils in isolated units (Woodruff 1954, Staple and Lehane 1955, Stoeckeler 1962, Van Eimern _et_ _al_. 1964, Pelton 1967, Lomas and Schlesinger 1970, Skidmore and Hagen 1970a, Radke and Hagstrom 1973, Blundell 1974, Marshall 1974, Hanson and Rauzi 1977). Many workers using the above techniques reported reduced potential evaporation behind windbreaks (Woodruff 1954, Staple and Lehane 1955, Stoeckeler 1962, Rosenberg 1966a, Pelton 1967, Skidmore and Hagen 1970a, Radke and Hagstrom 1973).

Stoeckeler (1962) found that a wood barrier with 50% porosity reduced evaporation 20% at 1 H declining to 0% at 10 H on the windward side, while evaporation was reduced 23% at 1 H, 35% at 3 H, declining to 6% at 25 H on the leeward side.

Radke and Hagstrom (1973), in their study, established double rows of corn as windbreaks after every 14 rows of soybeans. They observed reduced potential evaporation in the first seven or eight rows on the leeward side of the windbreaks. Higher potential evaporation rate occurred in the other eight to 14 rows, compared to the open area. They showed there was no significant difference in potential evaporation between sheltered and open area.

Skidmore and Hagen (1970a) found windbreaks of different porosities affected evaporation from wet surfaces differently. They found minimum evaporation leeward occurred at 4 to 5 H, 3.5 H, and immediately adjacent to windbreaks of 60, 40, and 0% porosities, respectively. Areas of leeward minimum evaporation coincided with areas of minimum wind speed. They also indicated that lowest relative evaporation over the observed region from 6 H windward to 12 H leeward was achieved with a 40% porous barrier.

Potential evaporation calculated from micrometeorological and climatological parameters also showed reduced potential evaporation behind windbreaks (Skidmore and Hagen 1970a, 1970b). Skidmore and Hagen (1970a) showed calculations of instantaneous evapotranspiration from micrometeorological parameters agreed fairly well with potential evaporation from atmometers behind windbreaks. Similarly, calculation of potential evaporation on a daily basis using climatological data from Dodge City, Kansas, showed a 31% average reduction from 1 to 10 H leeward of east-west oriented barriers. When the area was extended to 30 H, the average evaporation reduction decreased to 14% (Skidmore and Hagen 1970b).

Percentage reduction of potential evapotranspiration due to windbreaks is consistently less than the corresponding reduction in wind speed (Staple and Lehane 1955, Van Eimern et al. 1964, Pelton 1967, Skidmore and Hagen 1970b, Hanson and Rauzi 1977). Hanson and Rauzi (1977) observed in both South Dakota and Wyoming, that when wind was reduced by 50% or more by a windbreak, pan evaporation was reduced by about 14%.

Blundell (1974) placed evaporation tanks in unsheltered zones as well as at 10 and 20 H distances leeward from a shelterbelt of deciduous trees and showed that shelter had no significant effect on measured evaporation. There was a low positive correlation with wind and a large positive correlation with sunshine hours. Lomas and Schlesinger (1970) reported that under non-advective conditions the windbreak may not diminish evaporation although wind speed may be considerably reduced.

Similarly, Brown and Rosenberg (1972) used the Bowen energy balance method and Miller _et al_. (1973) used precision weighing lysimeters to show that under non-advective conditions, windbreaks did not reduce energy used in evaporation. On the other hand, under advective conditions, windbreaks reduced potential evaporation very significantly (Lomas and Schlesinger 1970, Brown and Rosenberg 1972, Miller _et al_. 1973).

Wind barriers may reduce actual evaporation less than potential evaporation because of two main reasons (Skidmore and Hagen 1970b). Low evaporative demand in shelter compared to open conditions, reduces the duration and degree of non-photolytically controlled stomatal closure of leaves in shelter grown plants and this phenomena causes increased transpiration compared to unsheltered plants. This results in less reduction in actual evaporation. Secondly, if the evaporating surface is not wet and the diffusion resistances are high, existence of a critical canopy resistance may not decrease evaporation when wind speed decreases (Monteith 1973). This may result in less reduction in actual evaporation than expected.

Rosenberg (1966a) observed potential evapotranspiration as indicated by evaporation from atmometers in the shelter of a two tiered snow-fence barrier was less than in unsheltered areas, but transpiration of beans and depletion of soil moisture in the shelter was greater than in the open. Skidmore _et al_. (1972) indicated that the Bowen ratio was small in sheltered areas, where according to their model evapotranspiration should have been greater.

Soil moisture. Two processes associated with windbreaks may benefit soil moisture. Properly designed permanent windbreaks and snow-fences in the middle and higher latitudes conserve soil moisture by catching and distributing snow (George *et al*. 1963, Stoeckeler 1964, Pelton 1967, Aase *et al*. 1978). Perennial barriers help in higher winter soil moisture recharge and result in higher wheat yields during average or below average rainfall years (Staple and Lehane 1955, Aase *et al*. 1978). Frank and Willis (1978), in their investigation to separate winter and summer effects on crop yield, showed yield of spring wheat was determined more by winter effects than by summer effects during normal years. But during dry years, summer effects also contributed to yield increase.

The reduction of potential evaporation below that which is normal in a region also contributes to soil moisture conservation. Aase and Siddoway (1976) showed that the drying rate from sheltered and exposed soil zones remained constant till noon after irrigation, thereafter drying rate was influenced by exposure to wind so that the drying rate in the sheltered zone was less.

Benefits of early water conservation by a windbreak resulted in early germination, rapid growth, larger plants, early complete cover of the soil, and a good root system in a bean experiment in western Nebraska (Rosenberg 1966a).

As the soils dry, crop cover decreases the relative importance of direct evaporation from soil. Transpiration becomes a major mechanism of water withdrawal. This indicates that the sheltered plots do not necessarily have more soil water than exposed plots. King (1970), Waister (1970), and Ogbuehi and Brandle (1982) reported that soil moisture was unaffected by shelter. Marshall (1974) showed that much of the time there was no difference in soil water content between the sheltered and exposed plots in Scotland.

Jensen (1954) in Denmark, and Mastinskaja (in Van Eimern *et al*. 1964) in the East Volga region of the USSR, showed that the initial soil moisture advantage of sheltered plants were eventually dissipated because sheltered plants transpired more water than unsheltered plants.

Carbon dioxide. Lemon (1970) suggested that low wind speeds would create low diffusion rates and consequently carbon dioxide supply to leaves might be reduced. Windbreaks reduced the turbulent transfer coefficient and this might adversely affect the rate of photosynthesis in a windbreak protected field. But Rosenberg (1966a) found that carbon dioxide supply did not affect the yield of beans under shelter.

Brown and Rosenberg (1972) found that the average carbon dioxide concentration above a sheltered sugar beet crop was 1 part per million lower and 3.5 parts per million higher than the corresponding carbon dioxide concentration in the open during the day and night, respectively. They also noted the differences in concentration of carbon dioxide were small even during a calm daytime period. Miller *et al*. (1973) observed that shelter in soybean field had no apparent effect on the carbon dioxide flux.

The Effect of Windbreak Modified Microclimate on Growth of Soybeans and Other Crops

Germination

The rate of germination and seedling emergence of soybeans are dependent upon soil temperature (Hatfield and Egli 1974, Hopper *et al*. 1979) and soil moisture (Hicks 1978). Higher soil temperature and moisture in the sheltered area may influence the germination and emergence of soybeans and other crops favourably.

Sturrock (1970a) reported that soybeans sheltered by temporary windbreaks in New Zealand germinated and grew rapidly due to favourable moisture and temperature conditions in the sheltered areas.

According to Rosenberg (1966b), rapid germination of sugar beets sheltered by temporary windbreaks in Nebraska was more likely due to increased soil moisture than to temperature modifications. Bagley (1964) also observed rapid germination of direct seeded tomatoes sheltered by temporary windbreaks. However, Rosenberg _et al_. (1967) did not find significant differences in germination of beans sheltered by snow-fence compared to open grown beans.

Vegetative Growth and Morphology

Temperature affects the rate of development and different growth parameters by soybeans (Brown and Chapman 1960, Hofstra 1972). Similarly, water stress also affects the growth and development of soybeans (Read and Bartlett 1972). Shelter-modified microclimate characterized by higher daytime and lower nighttime temperatures and reduced evaporative demand or water stress may influence the growth and development of soybeans and other crops.

Soybean plants in New Zealand responded to shelter-induced microclimate changes in increased leaf production and plant height within 2 to 3 weeks after erection of temporary windbreaks (Sturrock 1970a). Sturrock (1970a) also observed the mean total dry weight of the sheltered plants was twice that of the exposed plants, the greatest gain being in stem weight followed by leaf weight, root weight, and finally pod weight. Sheltered soybean plants also produced more roots than exposed plants and most sheltered plant roots were found in the upper horizon (Sturrock 1970a). He indicated higher soil moisture in the upper horizon of the sheltered area was responsible for better early growth, development of a larger leaf area, and an increased root production. The soil moisture extraction pattern indicated shallow-rooting species may be at a disadvantage in shelter (Sturrock 1970b). Shallow rooted larger plants in shelter, having exploited the better supply of soil moisture, were left at a greater disadvantage if soil moisture was not recharged by rainfall or irrigation (Rosenberg 1967, Sturrock 1970b). Rosenberg et al. (1967) also found early vigorous growth and larger bean plants in shelter, due to soil moisture conservation compared to slow growth of exposed plants.

In the sub-humid climate of Minnesota, Radke and Burrows (1970) reported soybeans sheltered by temporary corn windbreaks grew taller, produced more dry weight, and had a larger leaf area index compared to exposed plants. Dry matter production of soybeans in rows next to corn windbreaks was lower, but the dry matter production in the rest of the rows was higher than that of exposed plants and varied in cyclic fashion. The leaf area index followed a similar type of distribution.

Frank et al. (1974) observed increased plant height, dry matter, and green leaf area in sheltered soybeans compared to exposed plants, only if soil water was not limiting. Under dryland conditions shelter promoted early vegetative growth and increased leaf area, but the growth was later restricted due to water stress caused by rapid depletion of soil water by vigorously growing sheltered plants. They also reported that both irrigated and dryland sheltered plants had lower leaf density.

Even under rainfed conditions, soybeans grown in the shelter of permanent windbreak produced increased vegetative growth in Nebraska (Ogbuhei and Brandle 1981, 1982). Sheltered soybeans had a modified canopy structure compared to exposed plants with low leaf area density in the upper portion of the canopy. The modified canopy structure improved light distribution through the canopy (Ogbuhei and Brandle 1982). They claimed that improved light distribution through the canopy was partly responsible for increased yield of sheltered soybeans.

Similar improved vegetative growth patterns were observed in beans (Rosenberg 1966a, Rosenberg et al. 1967), tomatoes and beans (Bagley 1964), winter wheat (Aase and Siddoway 1974, Skidmore et al. 1974), spring wheat (Frank and Willis 1972, Frank et al. 1977a), sugar beets (Rosenberg 1966b, Marshall 1974), and turnips (Marshall 1974).

Early season higher soil temperature in the sheltered area of tall wheat grass accounted for early vigorous growth of winter wheat in Montana (Aase and Siddoway 1974), Higher temperatures in the sheltered zone of permanent windbreaks promoted early spring growth of perennial crops and extended their period of growth into autumn after the threshold temperature for growth had been reached in the open (Caborn 1957, Marshall 1967).

Both winter and spring wheats grew taller, produced more tillers, more dry weight, and larger flag leaf areas in sheltered areas than in open areas (Frank and Willis 1972, Aase and Siddoway 1974, Skidmore et al. 1974, Frank et al. 1977a). Skidmore et al. (1974) also observed that sheltered winter wheat had 24% less leaf chlorophyll in the flag leaf than those of the exposed wheat plants. Frank et al. (1977a) also noted an inverse relationship between leaf area index and leaf density was enhanced by shelter effects.

Growth analysis of sheltered and exposed turnips and sugar beets in Scotland showed mid-season divergence in dry matter production, and leaf area in favour of sheltered plants. Mid-season response in favour of shelter was further indicated by differences in crop growth rate in both turnips and sugar beets, and by relative growth rate and relative leaf growth rate in sugar beets. Sheltered sugar beet plants also had a higher net assimilation rate (Marshall 1974). Marshall (1974) concluded from his study that shelter affected vegetative growth and production through the effect of differential water stress produced by shelter. Due to lower water stress in shelter, plants produced larger leaf areas and had increased net photosynthesis (Marshall 1974).

Rosenberg (1966b) reported higher root/top ratios for sheltered sugar beets in Nebraska. But Marshall (1974) did not observe higher root/top ratios for sheltered sugar beets in Scotland, and suggested that the differences between shelter and exposed plants decreased from continental to oceanic climate. The same observation was reported earlier in regard to influence of shelter on many crops (Van Eimern _et_ _al_. 1964, Marshall 1967).

Differences in vegetative growth response between sheltered and exposed plants varied with soil moisture condition (Aase and Siddoway 1974, Frank _et_ _al_. 1974, 1977a, 1977b). Aase and Siddoway (1974) observed that the vegetative growth differences in winter wheat were masked at late growing stages, during years of ample rainfall. Frank _et_ _al_. (1974, 1977a, 1977b) showed that sheltered soybean and spring wheat showed vegetative growth responses to shelter under ample supply of soil moisture. But when moisture supply was restricted, sheltered plants showed early vegetative responses, followed by restricted growth compared to unsheltered plants. They also observed lower specific leaf weight under irrigated sheltered conditions, in spring wheat, which indicated that plants in sheltered areas were not under water stress, whereas dryland wheat had higher specific leaf weight because of water stress.

Crop cultivars differ in their vegetative growth response to shelter-induced microclimate. Felch (1964) reported large differences between varieties of _Phaseolus_ _vulgaris_ in their response to shelter-induced microclimate. Similarly, different cultivars of soybeans (Sturrock 1970b) and winter wheat (Skidmore _et_ _al_. 1974) showed differential vegetative growth responses to shelter. Rosenberg (1967) speculated that differences in response to shelter between cultivars could arise because of variations in varietal adaptability to the macroclimate.

Plant Water Relations

Wadsworth (1959, 1960), Whitehead and Luti (1962), and Whitehead (1962a, 1962b) suggested the observed effects of excessive wind speed on plants have often been the result of impaired water relations on plants. Plant water status is characterized by relative water content, relative opening of stomata, leaf and xylem water potentials, and stomatal diffusion resistance. Boyer (1970a, 1970b) indicated that as the leaf water potentials decreased, leaf enlargement was inhibited in soybeans. Boyer (1970a, 1970b) also indicated decreased leaf water potentials affected photosynthesis and dark respiration. This means higher leaf water potential as a result of reduced water stress enhances improved vegetative growth as indicated by taller plants, higher leaf area, and increased dry matter. As discussed earlier, windbreaks reduce potential evaporation, create a more favourable plant water status, and consequently, improve plant growth.

Frank *et al*. (1974) reported shelter with irrigation resulted in favourable plant water status in soybeans, as indicated by higher leaf and xylem water potentials and lower stomatal diffusion resistance compared to exposed irrigated plants. They, however, noted no difference in canopy temperature between sheltered and exposed irrigated plants. Under dryland conditions, there was little or no difference in leaf and xylem water potentials and stomatal diffusion resistance between sheltered and exposed plants. However, sheltered plants had higher canopy temperature compared to exposed plants.

Frank et al. (1974) reported that higher canopy temperatures due to reduced evapotranspiration of sheltered plants were indicative of greater plant water stress in sheltered plants.

Soybeans sheltered by permanent windbreaks in Nebraska also showed higher leaf water potential and stomatal conductance compared to exposed plants, even under rained conditions (Ogbuehi and Brandle 1981, 1982). They claimed the difference was due entirely to microclimate modifications by shelter, because they could not find significant differences in soil moisture status and plant water use between exposed and sheltered soybean plants.

Radke and Hagstrom (1973) found that differences in the average stomatal resistances between sheltered and exposed soybean plants were small. They reported that stomatal resistance was higher in the open during the early growing season, and higher in the sheltered area at pod filling and the seed set stage. They also observed stomatal resistance varied in a similar way to potential evapotranspiration. Both varied among rows with time on a daily and hourly basis. They could not establish that plant water relations were more favourable in sheltered plants than in exposed plants. They concluded that sheltered soybean vegetative growth and yield increases were largely due to an accumulation of the variations that occurred in the plant water relations during the growing season.

Radke and Burrows (1970) found that soybeans sheltered by corn windbreaks had increased vegetative growth and higher yield, but they could not relate those factors to an amelioration of moisture stress.

Shelter investigations on the growth of other crop species such as snap beans (Rosenberg et al. 1967), beans (Rosenberg 1966a), and turnips and sugar beets (Marshall 1974) showed higher relative water content and wider stomatal aperture in the sheltered plants compared to exposed plants.

Frank and Willis (1972) and Skidmore et al. (1974) reported higher leaf and xylem water potentials in sheltered wheat plants compared to exposed ones. Frank and Willis (1972) also noted higher stomatal diffusion resistance of sheltered spring wheat plants compared to exposed plants. The exposed plants, on the other hand, displayed constant minimal resistance throughout the day and thus seemed to have lost some of their potential for stomatal regulation.

Frank et al. (1977b) reported shelter plus irrigation in spring wheat improved plant water status compared to irrigation alone. They also reported that shelter alone did not alleviate the water stress of dryland grown wheat plants.

Skidmore _et al_. (1974) indicated that leaf water potential of sheltered winter wheat plants at intermediate stress was significantly higher than exposed plants. But shelter affected neither leaf water potential nor stomatal resistance when stress was low. Under high stress the leaf water potential did not differ significantly between sheltered and exposed plants.

Calculations of stomatal diffusion resistance with decreasing soil water potential by Brown and Rosenberg (1970) indicated that windbreaks may be more effective at greater water deficits. This data suggests that the influence of shelter and expected benefits in terms of productivity of the sheltered crop may be greater in arid regions.

Skidmore _et al_. (1974), in their study on the effect of shelter-induced microclimate on the performance of different varieties of winter wheat observed that the varieties differed in their response to shelter and exhibited differing plant water status. They also noted varieties with favourable plant water status under shelter had higher photosynthetic activity in shelter compared to exposed plants.

Water Use

Soybeans sheltered by corn and slat windbreaks in Minnesota did not show significant differences in water use compared to exposed plants (Radke and Burrows 1970). They suggested that this was due to the fact that the system did not have a closed bottom and the possibility of horizontal movement of water. Ogbuehi and Brandle (1981, 1982) also found no significant difference in plant water use between sheltered and exposed rainfed soybeans in Nebraska.

Lysimeteric studies by Miller et al. (1973) showed water use saving by soybean plants was greatest on days of strong sensible heat advection, but on days when advection was low the water saving was slight. The Bowen ratio of energy balance measurements above irrigated and sheltered sugar beets and for exposed sugar beets showed that daily water use rates did not differ greatly between sheltered and exposed sites (Brown and Rosenberg 1971, 1972). They found water use was more evenly distributed in shelter during the day, but water use in the open increased in the mid-afternoon with the onset of sensible heat advection.

Rosenberg et al. (1967) found that in a season of ample water supply, there was no difference in plant water use of snap beans.

Increased size of stomatal apperature and reduced stomatal resistance in shelter sometimes leads to greater transpiration of bean plants in shelter. This led to greater water use by sheltered beans compared to exposed beans (Rosenberg 1966a).

Water Use Efficiency

Reviews by Van Eimern et al. (1964) identified a great many experiments and observations in which water conservation was demonstrated. Both the Bowen energy balance method (Brown and Rosenberg 1971) and the lysimeteric method (Miller et al. 1973) have demonstrated little or no difference in water use between sheltered and exposed sugar beets and soybeans, respectively. Carbon dioxide flux measurements obtained from exchange coefficients derived from energy balance and lysimeteric methods suggested that photosynthetic flux rates were not greatly affected (Brown and Rosenberg 1971, Miller et al. 1973).

Generally, yields are superior in shelter. Therefore, wind barriers improved water use efficiency in shelter (harvestable yield per unit of water evaporated and transpired).

Ogbuehi and Brandle (1981) reported greater water use efficiency in soybeans. Bean production per hectare centimeter of water used was 58 kg for sheltered and 47 kg for exposed soybeans. Frank et al. (1977a) reported higher water use efficiency of irrigated sheltered wheat compared to irrigated wheat alone. But no difference was noticed in the water use efficiency of exposed and sheltered dryland wheat. Brown and Rosenberg (1972) explained theoretically that the large influence of a windbreak on water vapour content and negligible influence on carbon dioxide concentration, made the microclimate in shelter favourable to plant growth and increased water use efficiency.

Photosynthesis

Van Eimern et al. (1964) and Stoeckeler (1962) summarized evidence of increased plant growth in windbreaks reported by many researchers. There are few studies in which the rate of photosynthesis of sheltered and exposed crops have been compared.

Skidmore et al. (1974) observed higher photosynthetic rates of sheltered wheat varieties even though they showed reduced chlorophyll content in their leaves. Grace (1977) reported from unpublished data by Grace and Russel, that no detectable differences in photosynthesis were found between sheltered and exposed grass plots. Brown and Rosenberg (1970) reported that the mean difference in the stomatal diffusion resistance between sheltered and exposed plants explained a 6% increase in photosynthetic rate and as much as 25% yield difference in shelter as compared with no shelter in low yielding years.

Micrometeorological measurements in a sugar beet and soybean field indicated that shelter had no significant effect on the flux rates of carbon dioxide (Brown and Rosenberg 1972, Miller et al. 1973). Hence, photosynthesis was not affected by the presence of shelter.

Seed Yield

Windbreaks have been reported to increase the yield of many crops growing in the sheltered zone. Results from many researchers were published by Stoeckeler (1962), Read (1964), Van Eimern et al. (1964), and Radke and Hagstrom (1976).

Temporary crop barriers and snow-fences increased the yield of soybeans (Radke and Burrows 1970, Sturrock 1970a, Radke and Hagstrom 1973, Frank et al. 1974). Permanent windbreaks also increased the yield of soybean under rainfed conditions (Ogbuehi and Brandle 1981, 1982, and Baldwin 1982).

Sturrock (1970a) reported a 30% increase in seed yield of soybeans in New Zealand. Frank et al. (1974) reported that irrigated sheltered soybeans produced 17% more seed yield compared to irrigated exposed soybeans, while the sheltered dryland soybeans produced only an 8% increase in yield. Radke and Hagstrom (1973) reported only a mere 4 to 5% increase in seed yield of sheltered soybeans over exposed ones. Radke and Burrows (1970) showed a yield increase of -2.0 to 27.8% for different years, locations, varieties, and orientation of windbreaks. Ogbuehi and Brandle (1981) reported a 20 to 26% yield increase of sheltered soybeans over exposed ones under rainfed conditions.

Other crops which show yield increases include wheat (Staple and Lehane 1955, Pelton 1967, George 1971, Frank and Willis 1972, Skidmore et al. 1974, Aase and Siddoway 1974, Frank et al. 1977a), sugar beets (Rosenberg 1966b, Brown and Rosenberg 1970), tomatoes (Bagley 1964), beans (Bagley 1964, Felch 1964, Rosenberg 1966a, Rosenberg et al. 1967), and strawberries (Shah and Kalra 1970, Waister 1972). However, no yield increase was reported for wheat in some studies (Greb and Black 1961, Stoeckeler 1962, McMartin et al. 1974).

Within a species the range of response varied with location, season, type of windbreaks, and occasionally, with cultivars (Sturrock 1975). There is a tendency for crop yield increases to decrease in the wetter growing seasons and in more oceanic climates (Van der Linde 1962, Van Eimern et al. 1964, Marshall 1967, 1974). Similarly, in a given location, yield responses have been observed to be generally greater in dry years than in wet years (King 1970, Siddoway 1970).

Cultivars in a particular species also vary in their response to shelter, as indicated in beans (Felch 1964), soybeans (Sturrock 1970b), and winter wheat (Skidmore et al. 1974).

Sturrock (1970a) reported delayed maturation of sheltered soybeans in New Zealand compared to unsheltered plants. Felch (1964) also reported delayed maturation of beans. Bagley (1964) and Rosenberg et al. (1967), however, reported advanced maturation of sheltered tomatoes and beans.

Van Eimern et al. (1964) reported many investigations in which crop quality was increased in shelter. Caborn (1965) mentioned that shelter substantially increased the protein, starch, and vitamin C content of pasture in Hungary. In Manitoba, nitrogen uptake by strawberries was enhanced by tree shelter (Saha and Kalra 1970).

Mechanical Stress

Excessively strong winds cause mechanical, morphological, anatomical, and physiological stresses to plants.

Mechanical damage is expressed in the form of lodging of whole plants, branches, loss of leaf area, abrasive damage (Waister 1972), leaf scorching or necrosis, and even disruption and smoothing of epicuticular waxes (Thompson 1974). Yet another possibility is that the plants respond directly to the effect of shaking (Neel and Harris 1971, Turgeon and Webb 1971, Parkhurst and Pearman 1972, Jaffe 1973). Khal (1951) indicated that shaken tissues and cells had higher respiration and lower photosynthesis due to disruption of plasma. Todd *et al*. (1972) reported that dark respiration of many species increased with an increase of wind speed.

If it assumed that these effects, and the damage from mechanical injury are significant under field conditions, part of the benefits of windbreaks would be due to the alleviation of mechanical stress.

MATERIALS AND METHODS

Experimental Material

The soybean cultivar, McCall, was used both in 1981 and 1982 experiments. This cultivar was used because it is the high yielding, indeterminate, and less photoperiod sensitive variety recommended for areas in Manitoba which have frost-free periods of 125 days or more and which accumulate at least 2400 corn heat units (Field Crop Recommendations for Manitoba 1981). It matures in about 111 to 136 days.

Pedigreed seed of certified status was used in both years. In 1981, seed was obtained from "Kroeker Farms", whereas in 1982, seed was obtained from Manitoba Pool Elevators.

The sunflower hybrid, Cargill-204, was used as the annual windbreak in both years to provide shelter for soybeans. Cargill-204 was used because it is one of the recommended hybrids for southern Manitoba, which has good resistance to lodging and to many diseases. It grows to a height of about 175 cm and matures in 116 to 122 days.

In 1981, Cargill-204 seed was obtained from a commercial seed stock with a germination in the range of 75 to 85%. In 1982, Cargill-204 seed was obtained from Cargill Grain Company Limited.

Experimental Site

In both 1981 and 1982, the experiments were conducted at the Department of Plant Science field station, Portage la Prairie. This area has more than 125 frost-free days. The average growing degree days above 5° C and the corn heat units for this area, are 1600 to 1700 and 2400 to 2500, respectively. Average growing season precipitation is 325 mm. During the summer months, the most frequent wind speed ranges from 4 to 23 km/hr and wind direction is indeterminate as indicated in Tables 1 and 2.

The soil type was a Gnadenthal loam (Michalyna and Smith 1972), the top soil had a particle size distribution of 14% sand, 51% silt, and 35% clay.

In 1981, the north-south oriented windbreak experiment was situated on summer fallow, whereas in 1982, it was situated on barley stubble. The east-west oriented windbreak, the second experiment in 1982, was situated on land which had been sown to sudan grass in 1981.

Experimental Procedure

The experiments were designed to determine the response of soybeans to annual windbreaks of different permeabilities, obtained by using one and two rows of sunflowers. Sunflowers were selected as an annual crop windbreak because of its compatability with soybeans in planting and weed control practices. The experiment consisted of three treatments which were as follows:

Treatment 1 : Zero row of sunflower windbreak.
Treatment 2 : One row of sunflower windbreak.
Treatment 3 : Two rows of sunflower windbreak.

Because summer wind direction at Portage la Prairie is indeterminate, and because annual windbreaks favourably modify microclimate up to a distance of 10 to 12 H leeward, north-south oriented parallel windbreaks were established 12 H or 15 m apart to provide shelter for soybeans in the main experiments, since H, the effective height of windbreak, was assumed to be 120 cm. Also, since annual windbreaks have little or no influence on microclimate beyond a leeward distance of 20 to 25 H, replicates were separated

TABLE 1. Monthly percentage wind speed frequencies for the growing season at Portage la Prairie, (mean of 20 years: 1953-1972).

		Wind Speed km/hour								
Month	Calm	0-3	4-6	7-12	13-17	18-23	24-29	30-35	36-40	41-46
	%									
May	5.4	3.3	13.6	33.1	24.0	14.7	4.3	1.3	0.2	0.0
June	6.7	5.0	18.7	36.8	20.6	9.3	2.5	0.5	0.1	0.0
July	8.6	5.9	20.8	39.2	17.1	6.7	1.3	0.4	0.0	0.0
August	8.6	6.1	20.5	38.7	17.3	7.1	1.3	0.3	0.0	0.0
September	6.1	4.8	16.6	38.8	21.5	9.5	2.2	0.4	0.1	0.0

TABLE 2. Monthly percentage wind direction for the growing season at Portage la Prairie, (mean of 20 years: 1953-1972).

Month	Calm	Wind Direction															
		NNE	NE	ENE	EAST	ESE	SE	SSE	SOUTH	SSW	SW	WSW	WEST	WNW	NW	NNW	NORTH
	%																
May	5.4	6.3	3.5	3.2	4.3	5.2	5.8	7.4	6.2	4.4	4.7	5.2	4.3	5.1	4.8	10.6	13.8
June	6.7	5.7	3.3	2.8	3.3	3.9	6.5	9.5	7.7	4.7	5.4	7.0	6.5	6.8	4.8	6.7	8.9
July	8.6	4.1	2.8	2.3	2.7	3.5	4.4	7.8	7.2	5.0	6.1	8.1	9.2	8.5	5.8	6.5	7.3
August	8.6	5.0	2.8	2.3	3.4	4.8	6.3	9.4	7.1	4.4	4.9	7.1	6.6	7.2	5.8	5.8	8.5
September	6.1	3.8	2.2	1.6	2.5	4.0	6.3	9.0	7.3	5.3	5.8	7.8	9.0	8.8	7.3	6.5	6.7

by a distance of 20 H or 25 m to prevent the influence of the windbreak of one replicate on another.

Windbreaks of 35 and 30 m length were planted in 1981 and 1982, respectively, to provide full shelter to the soybean plants in the middle 5 m strip between the parallel windbreaks even when wind came from a direction which was not perpendicular to the windbreaks. Figure 1 shows the detailed layout of one block of the 1981 experiment. The 1982 main experiment was identical in layout except as noted above.

Both in 1981 and 1982 for the main experiment, soybeans were seeded in north-south oriented rows 55 cm apart in an area of approximately 2 hectares with a John Deere Model 71 Flexi-planter. Soybeans were seeded on May 26 and 27 in 1981 and on May 21 and 22 in 1982. Sunflowers were also seeded with soybeans in a single operation with the same seeding equipment. Sunflowers replaced one row or two rows of soybeans and formed parallel windbreaks for every 26 rows of soybeans for the one row windbreak or for the two row windbreak treatment, respectively. At least 10 rows of soybeans were left on either side of the experimental area as borders. The 26 rows of soybeans within a plot were numbered 1 to 26 from the east side of the west windbreak and row numbers were used to identify sampling locations.

The soybeans were treated with a commercial preparation of *Rhizobium japonicum* inoculum 'Nitragen-S' and seeded at a rate of 130 kg/ha.

Because the sunflowers were seeded very thickly with soybean seeding equipment, the sunflower stand was thinned to 8 to 10 plants per meter at emergence.

Fertilizer and herbicides were applied at recommended rates as summarized in the Appendices 1 and 2.

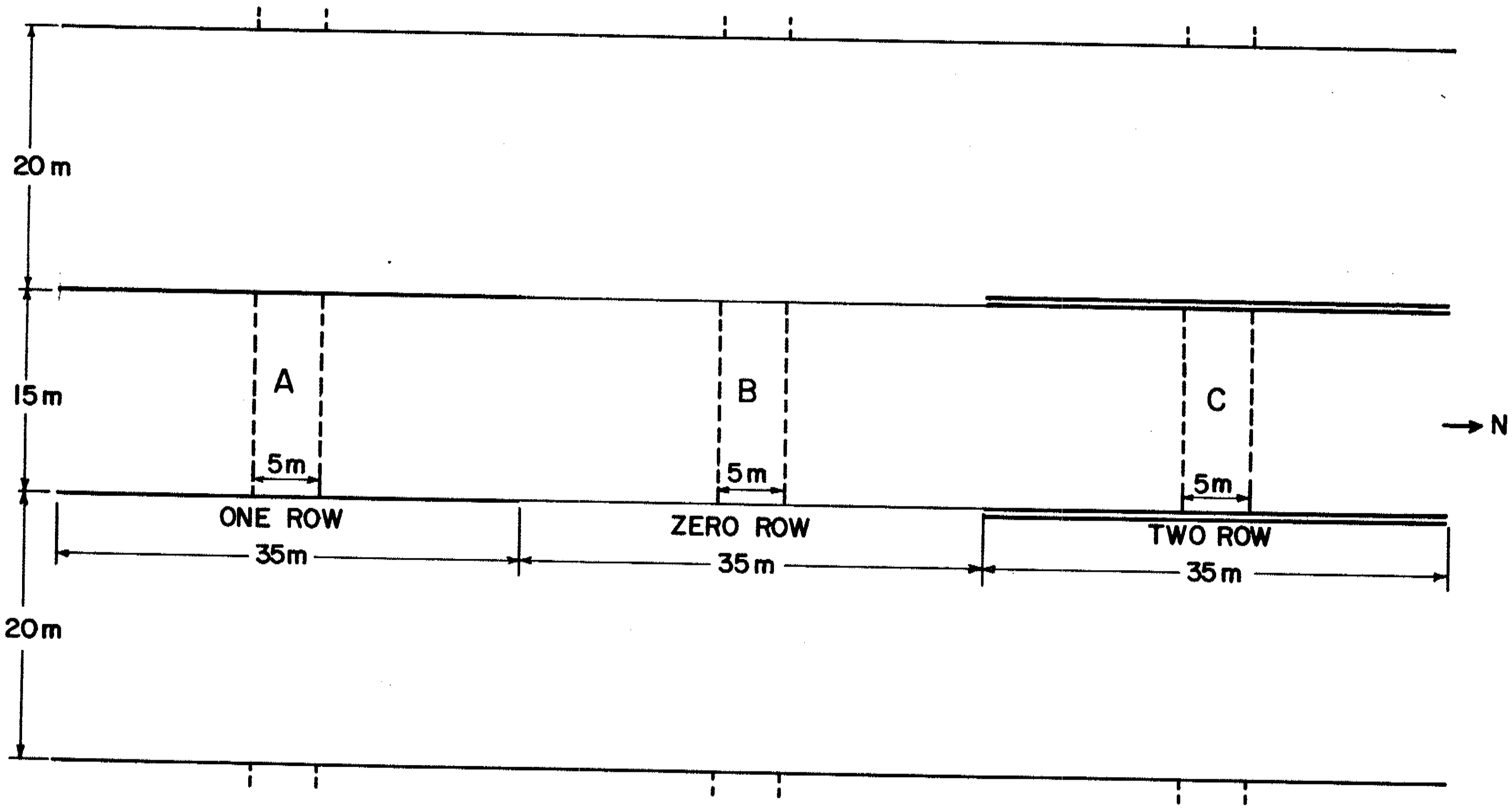

Figure 1. Typical plot layout of the north-south oriented windbreak experiment with detailed layout of one block showing the area harvested for yield (A, B, and C).

The north-south oriented windbreak experiment formed the main experiment in both years. In 1982, a second experiment with similar objectives as the main experiment, was conducted with windbreaks oriented in an east-west direction.

Experimental Design

The main experiment in both years was conducted as a randomized complete block design with three treatments and five replicates. The second experiment in 1982 was also conducted as a randomized complete block design with three treatments and three replicates.

Plant Response Observations

Phenological Development

Microclimatic parameters affect soybean growth differently at different stages of growth. The developmental stages of each plot were recorded periodically and used to derive the number of days required to attain a specific growth stage from seeding for each plot. The growth stages of each plot were determined by standards graphically outlined in a special report by Fehr and Caviness (1977). Vegetative and reproductive stages are described in Appendices 3 and 4, respectively. A plot was considered to have attained a given stage of growth when 50% of the observed plants had achieved that stage. The number of days required to reach a growth stage by the replicates were averaged to provide a mean value for each treatment.

Plant Height

Commencing from the middle of July, plant heights of both soybeans and sunflowers were measured periodically until soybeans produced a terminal inflorescence and the sunflowers produced flower heads. Soybean plant height was recorded as the height of the plant to the topmost node with fully opened leaves. The sunflower plant height was recorded as the height of the plant to the tip of the terminal bud. The height differences between soybeans and sunflowers gave the effective windbreak height for different sampling dates.

Soybean plant heights were measured from 10 randomly selected plants from each row. Five to 10 rows were selected for each sampling date in such a way that the whole plot was sampled adequately. Rows 1 and 26 were not included in the sample.

Sunflower plant heights were measured from 25 randomly selected plants from each row. Random selection of plants was done in such a way to cover the whole length of windbreak.

Leaf Area

Six half-meter row samples were taken both in 1981 and 1982 to measure leaf area. A half-meter row sample per row was randomly selected either from left or right of the middle 5 m strip. The six samples were taken from rows 3, 7, 11, 15, 19, and 23. No samples were taken from rows 1 and 26.

In 1981, the first sample was taken at the fifth node stage. A second sample was taken between the beginning of podding and the full pod stage. In 1982, only leaf weight was recorded for the first sample taken at the fifth node stage. Leaf area was recorded for both the second and third samples taken between the beginning of podding and the full pod stage and between the beginning of seed development and full seed stage, respectively.

Half meter row samples were cut and immediately stored in coolers. Later, the leaflets were separated from the plants and their area measured in square centimeters using a Lamda leaf area meter, Model L1-3000. Leaf area is reported as leaf area index and was obtained by dividing the leaf area above by 2750 cm^2.

In 1982, leaves which were used to determine leaf area were also subsequently oven dried to determine leaf dry weights.

Top Dry Weight

Six half-meter row samples were taken in both years to determine the top dry weight of soybean plants. The procedure used to select samples for leaf area was followed to select samples for dry weight.

Both in 1981 and 1982, the first sample was taken at the fifth node stage, while the second sample was taken between the beginning of podding and the full pod stage. In 1981, a third sample was taken at the full seed stage, whereas in 1982, it was taken between the beginning of seed development and the full seed stage and a fourth sample was taken at the full seed stage.

Samples were cut and frozen on the sampling day. Later, the samples were oven dried at 60 to 70° C for more than 72 hr, then dry weights were determined. Dry weights are reported in grams per meter of row.

Pod Number Per Plant

Pods from 24 randomly selected plants were counted to record number of pods per plant. One plant per row was randomly selected from rows 2 to 25 to give 24 plants.

Seed Yield

Both in 1981 and 1982, the middle 5 m strip was harvested manually for seed yield determination. Each 5 m row was treated as a sample and harvested and threshed separately to determine yield on a 5 m row basis. Total plot yield is reported as the total seed weight of the 25 x 5 m row samples combined.

Seed Weight

Three seed samples were taken from each plot, weighed and the number of seeds counted to determine 1000 seed weight.

Seed Quality

The seed samples used to determine 1000 seed weight were used to determine oil and protein content of seed. Oil content was determined by NMR (Nuclear Magnetic Resonance) analysis and reported as oil percentage. Protein content was determined by Kjeldahl procedure and reported as (N x 6.25) percent. Both values are reported on a whole seed zero moisture basis.

Microclimatic Observations

Soil Moisture

Volumetric soil moisture content to a depth of 120 cm was determined periodically to detect the differences in plant water use between treatments.

Soil moisture was determined in both years at three locations within a plot to a depth of 120 cm. The three locations selected were between rows 5 and 6, 13 and 14, and 21 and 22, respectively.

Soil rings of known volume (23.89 cc) were used to take soil samples of known volume at four depth intervals in the top 20 cm to determine the volumetric soil water content of the top 20 cm of the soil. The depth intervals were 0 to 5, 5 to 10, 10 to 15, and 15 to 20 cm. Wet and dry weights of the known volume of soil were determined before and after the soil was dried in a convection oven for 48 hr or more at 110° C, respectively. Wet and dry weights were used to calculate gravimetric soil moisture content. Gravimetric moisture content and bulk density were used to determine volumetric moisture content.

Volumetric moisture content of the 20 to 120 cm sample was determined with a Neutrone probe. In each plot, three aluminum access tubes (51 mm O.D.) were placed in the sampling location to a depth of 140 cm. Volumetric soil moisture content was monitored at 20, 50, 80, and 110 cm depths.

Water use of soybean plants was calculated using the difference in total water content of the 0 to 120 cm soil profile between two sampling dates and the amount of precipitation received between the sampling dates.

Canopy Air and Air Temperatures

In both years, canopy air and air temperatures were monitored with thermocouples shielded from direct solar radiation. Canopy air and air temperatures were monitored in two positions, in the middle of the canopy and 25 cm above the canopy, respectively. Thermocouples were periodically adjusted with the growth of the soybeans to maintain their respective positions continuously.

Temperatures were monitored in one replicate and three locations within a plot in 1981, whereas in 1982, temperatures were monitored in two replicates and in two locations within a plot. Thermocouples mounted on wooden stakes were positioned between rows 3 and 4, 12 and 13, and 22 and 23 in 1981, and between rows 8 and 9 and 18 and 19 in 1982, respectively.

A Campbell Scientific CR5 Digital Recorder was used in both years to monitor temperatures at 3 hr intervals.

East-West Oriented Windbreak Experiment

Planting and other cultural practices were carried out similar to the north-south oriented windbreak main experiment.

All plant response observations determined in the main experiment were also determined in this experiment, except the leaf area was measured only once between the beginning of seed development and the full seed stage and top dry weight was only determined twice, once between the beginning of the seed development stage and the full seed stage and again at the full seed stage.

No micrometeorological observations were made on this experiment.

Statistical Analyses

Plant response observations were analyzed using an analysis of variance procedure for a randomized complete block design. Mean values for the samples from an experimental unit were used as the value for that experimental unit and used in the analyses.

Seed yield data was also analyzed using an analysis of variance appropriate for a split-block design with five sub-blocks to detect the extent of unfavourable influence of windbreaks on seed yield. Soybean rows 1 and 2, 5 and 6, 12 and 13, 20 and 21, and 25 and 26 formed the five sub-plots within a plot for each treatment.

Significant differences among treatment means were detected using a Duncan's Multiple Range test. An alpha level of 5% was used to detect statistically significant differences.

Canopy air and air temperatures were not subjected to statistical analysis of variance. Temperature data are presented graphically and the trends examined.

RESULTS AND DISCUSSION

Microclimate During the 1981 and 1982 Growing Season

Temperature, precipitation, and wind speed and direction that prevailed during the 1981 and 1982 growing season, May through September, are indicated in Tables 3, 4, 5, and 6.

The temperature data in 1981 indicated that the mean temperature in July and August was higher than normal, whereas June temperature was lower than normal. The mean temperature in May and September was near normal.

The temperature data in the 1982 growing season indicated that the mean temperature in May was higher than normal, whereas in June and August, the mean temperature was lower than normal. The mean temperature in July and September was near normal.

Comparison of the 1981 and 1982 growing season temperatures indicated that the 1981 growing season was warmer than the 1982 growing season.

Precipitation records indicated that the 1982 growing season was wetter than the 1981 growing season.

Wind speed frequency data indicated that the wind speed varied from 6 to 28 km/hr for most of the time during the 1981 and 1982 growing seasons. Wind direction records indicated that the wind direction was indeterminate during the 1981 and 1982 growing seasons.

TABLE 3. Maximum, minimum, and mean temperatures and precipitation for the growing season at Portage la Prairie in 1981.

Date	May				June				July				August				September			
	Temperature °C[1]			Rain[2] mm	Temperature °C			Rain mm	Temperature °C			Rain mm	Temperature °C			Rain mm	Temperature °C			Rain mm
	Max.	Min.	Mean		Max.	Min.	Mean		Max.	Min.	Mean		Max.	Min.	Mean		Max.	Min.	Mean	
1	15.7	- 2.4	6.7		20.9	10.5	15.7		29.9	17.7	23.8		24.8	11.5	18.2		20.0	5.0	12.5	
2	19.2	8.9	14.1		22.8	4.8	13.8		26.0	16.1	21.1		26.3	14.5	20.4		2.44	9.6	17.0	
3	11.8	3.6	7.7		27.0	4.3	15.7	12.4	28.6	13.5	23.9		24.4	14.4	19.4	6.6	15.0	3.8	9.4	
4	11.2	0.6	5.9		21.7	12.1	16.9		31.4	16.4	24.8		29.0	13.6	21.3	0.1	20.5	2.3	11.4	
5	13.7	- 3.8	5.0		23.7	12.0	17.9		30.6	18.9	26.3		21.6	16.8	19.2	55.9	23.6	12.3	18.0	
6	18.4	- 2.2	8.1		23.7	9.1	16.4		37.2	15.3	28.8		25.4	16.9	21.2		18.4	10.9	14.7	
7	20.6	3.0	11.8		22.8	12.3	17.6		35.0	22.6	21.1		29.0	15.2	22.1		22.7	8.9	15.8	
8	15.1	- 1.2	7.0		19.3	9.2	14.3	4.6	27.6	24.6	21.1		21.5	11.9	16.7		26.1	8.3	17.2	
9	8.7	- 4.2	2.3		18.9	7.6	13.3	3.8	30.3	11.8	21.3		23.0	10.6	16.8	1.3	27.8	12.9	20.4	
10	12.1	- 0.5	5.8		19.2	7.3	13.3		29.1	13.4	21.1		27.1	13.5	20.3		34.0	14.4	22.7	
11	17.2	4.1	10.7		21.3	6.9	14.1		27.5	14.7	23.0		32.7	16.0	24.4		25.3	11.6	18.5	
12	20.3	0.3	10.3		25.6	7.1	16.4		29.8	16.2	23.5	3.6	26.1	13.3	19.7		24.2	9.9	17.1	
13	21.8	- 0.8	10.5		20.5	13.9	17.2		30.4	16.5	19.5		33.3	14.0	23.7		21.2	7.9	14.6	
14	22.9	1.8	12.4		17.2	12.9	15.1	19.7	22.9	16.0	19.6	0.1	23.1	12.0	17.6		17.6	6.5	12.1	
15	16.3	5.1	10.7		13.9	7.5	10.7	8.1	23.3	15.9	17.8	19.3	21.9	9.0	15.5		13.3	6.3	9.8	
16	17.5	2.2	9.9		25.2	6.6	15.9		22.4	13.1	19.1		24.2	6.3	15.3		13.0	6.1	9.6	
17	22.2	3.5	12.9		19.5	11.5	15.5	8.4	24.8	13.4	20.5		29.2	14.6	21.9		19.8	3.5	11.7	
18	24.8	2.8	13.8		17.7	8.4	13.1		27.1	13.8	21.4		30.3	14.2	22.3		23.6	7.4	15.5	1.3
19	26.8	10.8	18.8		21.2	7.0	14.1	0.6	27.8	15.0	16.0		31.2	14.4	22.8		19.9	5.0	12.5	
20	28.9	9.2	19.2		22.8	9.0	15.9		20.9	11.0	16.1		28.7	13.9	21.3		19.8	1.6	10.7	
21	30.4	10.3	20.3		20.0	9.0	14.5		23.9	8.2	16.9		27.2	16.9	22.1		17.1	7.6	12.4	
22	22.0	5.8	13.9		20.4	11.7	16.1		24.0	9.7	21.6		27.6	14.6	21.1		15.4	3.1	9.3	
23	7.3	- 5.3	6.3		21.0	9.5	15.3	4.4	29.7	13.5	16.4		27.0	18.4	22.7	14.2	20.9	6.5	13.7	
24	8.9	6.8	7.9	28.7	23.4	12.0	17.7		19.8	12.9	14.3		27.6	18.4	23.0		20.9	4.1	12.5	
25	14.2	8.2	11.2		22.8	12.0	17.4	1.7	21.1	7.5	15.9		27.2	16.8	22.0		19.4	3.7	11.6	
26	20.7	4.9	12.8		26.9	10.0	18.5		25.0	6.8	18.5		27.8	16.9	22.4		16.3	3.9	10.1	
27	20.2	7.2	13.7		28.5	15.5	22.0		26.2	10.7	18.5		26.8	12.1	19.5		9.4	- 1.5	3.4	29.0
28	23.3	12.2	27.8	8.1	22.3	12.8	17.6	9.4	26.3	13.3	19.8		27.3	12.4	19.9		2.9	- 1.7	0.6	4.8
29	17.4	3.2	10.3		24.6	10.9	17.8		26.1	14.6	20.4	0.9	30.1	12.3	21.2		12.6	0.8	6.7	0.5
30	18.8	0.8	9.8		27.6	13.4	20.5	15.7	28.3	15.6	22.0	25.6	31.3	13.6	22.5	4.6	7.8	2.8	5.3	7.9
31	22.3	6.6	14.5						24.0	13.2	18.6		23.6	8.9	16.3					
	18.4	3.6	11.0	36.8	22.9	9.9	16.0	88.8	27.0	13.9	20.5	49.5	27.0	13.8	20.4	82.7	19.0	6.0	12.5	43.5

[1] From Canadian Forces Base, Portage la Prairie.

[2] From the field station, Portage la Prairie.

TABLE 4. Maximum, minimum, and mean temperatures and precipitation for the growing season at Portage la Prairie in 1982.

	May				June				July				August				September			
	Temperature °C[1]			Rain[2] mm	Temperature °C			Rain mm	Temperature °C			Rain mm	Temperature °C			Rain mm	Temperature °C			Rain mm
Date	Max.	Min.	Mean		Max.	Min.	Mean		Max.	Min.	Mean		Max.	Min.	Mean		Max.	Min.	Mean	
1	23.7	0.3	12.0		13.2	4.4	8.8		27.6	8.5	18.1		21.3	11.3	16.3		16.7	6.6	11.7	2.3
2	28.3	6.1	17.2		17.6	- 0.2	8.7		24.3	17.1	20.7		22.3	16.0	19.2		20.8	8.4	14.6	
3	28.3	15.7	22.0		24.9	4.4	14.7		30.0	16.8	23.4	10.4	30.4	14.0	22.2		27.9	6.8	17.4	
4	21.8	7.8	14.8		24.1	10.7	17.4		31.6	14.0	22.8		25.5	15.3	20.4		20.8	11.2	16.0	
5	17.8	4.1	11.0		25.7	14.3	20.0	21.6	27.6	17.4	22.5	5.3	27.5	11.9	19.7		17.2	8.1	12.7	
6	10.3	0.3	5.6	1.3	16.4	12.1	14.3		24.0	12.4	18.2		28.2	18.1	23.2		15.3	6.9	11.1	
7	8.0	0.6	4.3		14.2	3.2	8.7	3.8	22.9	9.0	16.0		25.8	15.0	20.4	3.8	27.1	6.2	16.7	
8	7.6	- 0.4	3.6	1.3	11.2	0.4	5.8		23.8	9.8	16.8	0.3	20.2	11.8	16.0		30.1	11.9	23.0	
9	13.5	2.4	8.0		17.0	6.8	11.9		25.3	14.5	19.9		17.8	9.0	13.4		34.3	14.6	24.5	
10	8.1	5.7	6.9	11.2	24.2	4.4	14.3		26.2	14.4	20.3	3.8	21.5	5.6	13.6		32.3	10.4	21.4	
11	16.4	5.0	10.7		17.2	7.9	12.6		27.5	12.5	20.0		25.2	8.4	16.8		23.7	7.8	15.8	
12	17.6	1.7	9.7		24.3	4.1	14.2	0.8	28.2	15.2	21.7	6.1	20.3	14.1	17.2	1.3	20.0	5.6	12.8	
13	19.9	5.9	12.9		24.7	9.6	17.2		20.8	14.6	17.7	0.3	27.7	14.1	20.9		15.8	7.8	11.8	
14	21.9	8.3	15.1		21.2	8.7	15.0		24.9	9.4	17.2		31.0	15.1	22.6	23.4	11.3	- 0.8	5.3	
15	13.1	8.8	11.0	10.7	20.4	6.3	13.4	0.8	29.8	18.2	24.0	20.3	24.4	14.2	19.3		15.2	- 2.9	6.2	
16	14.0	9.9	12.0		22.9	10.3	16.6		25.3	16.4	20.9		26.0	14.4	18.7		20.8	5.2	13.2	
17	12.5	9.4	11.0	7.6	13.7	6.4	10.1		22.1	12.6	17.4		29.9	12.8	20.4	2.0	13.5	5.8	9.7	2.8
18	14.9	8.8	11.9		18.9	8.5	13.7		23.7	9.4	16.6	25.7	28.7	16.9	22.8	0.8	21.4	7.9	14.7	
19	13.9	7.5	10.7		15.8	10.3	13.1	6.9	26.8	12.5	19.7		26.1	13.6	19.9		13.2	1.7	7.5	3.1
20	19.6	6.0	12.8		19.8	8.9	14.4		25.3	16.0	20.1		25.6	11.9	18.8		17.8	0.1	9.0	
21	22.3	4.2	13.3		20.2	7.5	13.9		22.8	12.8	17.8		23.8	13.7	18.8	17.3	23.4	5.8	14.6	
22	24.7	6.1	15.4		19.5	7.8	13.7	0.8	23.2	11.7	17.5	4.6	21.8	12.3	17.2		24.4	4.4	14.4	0.6
23	25.5	6.3	15.9		28.7	11.5	20.1		26.8	16.8	21.8		22.1	9.1	15.6		14.4	9.1	11.8	
24	21.5	11.5	16.5		18.0	6.9	12.5		27.7	17.5	22.6		18.3	11.0	14.7	0.3	14.0	1.0	7.5	
25	26.3	8.8	17.6		23.2	4.2	13.7		24.6	14.5	19.6		13.0	4.2	8.8		18.4	3.0	11.7	
26	27.8	13.1	20.5		25.2	12.7	19.0	0.5	27.5	12.6	20.1	34.5	16.0	3.2	8.4		15.1	5.8	10.5	
27	28.1	12.0	20.1		23.4	10.8	17.1		25.3	15.7	20.5		14.9	1.4	8.2		7.4	4.4	5.9	36.5
28	22.9	11.5	17.2		21.0	10.5	15.8		26.9	12.8	19.9	43.2	20.7	4.9	12.8		13.2	4.6	8.9	8.0
29	19.3	8.2	13.8	2.3	19.6	6.4	13.0		23.2	12.2	17.7		19.7	5.6	12.7		10.8	3.9	7.4	
30	16.2	6.9	11.6		24.0	4.2	14.1		26.3	12.9	19.6		17.1	4.5	10.8		7.9	1.4	4.7	
31	11.3	3.4	7.4	0.3					30.0	15.9	23.0		24.5	8.3	16.4					
	18.6	6.7	12.7	34.7	21.0	7.5	13.9	35.2	25.9	13.7	19.8	154.5	23.1	10.9	17.0	48.9	18.8	5.9	12.4	53.3

[1] From Canadian Forces Base, Portage la Prairie.

[2] From the field station, Portage la Prairie.

TABLE 5. Percentage wind speed frequencies for the growing season in 1981 and 1982 at Portage la Prairie.

		Wind Speed Frequencies km/hr						
Month	Calm	1-5	6-11	12-19	20-28	29-38	39-49	50-61
					%			
May 1981	9	8	34	28	17	4	+	
1982	6	5	31	34	20	4	+	
June 1981	5	4	44	30	11	4	2	
1982	9	5	34	30	17	5	+	+
July 1981	9	4	37	32	13	5	+	
1982	11	5	36	28	16	3	1	+
August 1981	13	3	42	28	10	4	+	
1982	9	5	34	30	16	5	1	
September 1981	7	4	33	29	20	5	1	1
1982	-	-	-	-	-	-	-	-

TABLE 6. Percentage wind direction for the growing season in 1981 and 1982 at Portage la Prairie.

		Wind Direction															
Month	Calm	NORTH	NNE	NE	ENE	EAST	ESE	SE	SSE	SOUTH	SSW	SW	WSW	WEST	WNW	NW	NNW
									%								
May 1981	9	19	5	4	5	7	6	5	6	8	7	3	3	5	2	2	4
1982	6	8	5	8	5	4	5	6	7	8	3	3	4	7	5	7	9
June 1981	5	7	4	3	2	4	4	6	6	8	4	5	7	15	10	6	4
1982	9	17	5	1	1	1	2	4	8	5	5	4	6	9	7	8	8
July 1981	9	6	3	1	1	3	6	8	9	12	6	6	8	12	6	2	1
1982	11	5	3	2	1	5	8	6	7	4	2	8	8	10	8	7	5
August 1981	13	8	3	2	3	5	6	8	9	8	4	3	5	4	6	7	6
1982	10	7	3	1	1	3	7	9	10	6	3	3	3	10	10	8	6
September 1981	7	6	3	1	2	6	10	10	7	4	2	5	5	8	10	7	6
1982	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

North-South Oriented Windbreak Experiment

Phenological Development

The rate of development, as indicated by the number of days to reach a phenological growth stage from seeding, was not significantly different for any of the three treatments in either 1981 or 1982 (Table 7).

Vegetative development, as indicated by the number of days from seeding to the fifth node stage (V_5) took approximately 41 and 50 days in 1981 and 1982, respectively. Similarly, the reproductive stages as indicated by the number of days to reach flower initiation (R_1) and full seed stage (R_6) from seeding took 42 and 99 days in 1981 and 54 and 104 days in 1982, respectively.

Temperature is the major factor influencing the rate of vegetative development. Fehr and Caviness (1977) reported that temperature influences the rate of vegetative development up to the fifth node stage. Because the windbreaks did not provide full shelter until the beginning of the seed formation stage (R_5), the vegetative developmental stages were not influenced by the shelter modified microclimate. Hence, the three treatments took more or less the same number of days to reach the fifth node stage in both years.

Fehr and Caviness (1977) also reported that temperature and day length influence the rate of reproductive development. In 1981, air temperatures monitored from the full bloom (R_2) stage showed that the differences between treatments were small. Similar trends were observed in air temperatures monitored from the second node stage (V_2) in 1982. The rate of reproductive development of the three treatments were similar in 1981 and 1982 and not affected by windbreaks because the temperature differences were too small to have an appreciable effect on the rate of reproductive development (Tables 8 and 9).

TABLE 7. Number of days to reach a phenological growth stage from seeding by zero, one, and two row windbreak treatments in 1981 and 1982.

Treatment		Growth Stages[1]								
		VE	VC	V1	V5	R1	R3	R5	R6	R7
		days								
Zero Row	1981[2]	11	14	24	41	42	59	73	99	114
	1982[3]	11	15	27	50	54	68	81	104	*
One Row	1981	11	14	24	41	42	59	73	99	115
	1982	11	15	27	50	54	68	81	103	*
Two Row	1981	11	14	24	41	42	59	73	99	114
	1982	11	15	27	50	54	68	81	104	*

[1] Growth stages defined in Appendices 4 and 5.

[2] Soybeans seeded on May 26 and 27, 1981.

[3] Soybeans seeded on May 21 and 22, 1982.

* Frost damaged before reaching this stage.

TABLE 8. Weekly mean air temperatures for zero, one, and two row windbreak treatments in 1981.

Treatment	Week Number							
	1*	2	3	4	5	6	7	8
	°C							
Zero Row	16.5	17.9	17.8	17.4	18.4	18.6	13.5	16.3
One Row	16.4	17.8	17.9	17.6	18.5	18.5	13.3	15.8
Two Row	16.6	18.3	17.9	17.4	18.5	18.6	13.3	15.4

*From July 22, 1981.

TABLE 9. Weekly mean air temperatures for zero, one, and two row windbreak treatments in 1982.

Treatment	Week Number												
	1*	2	3	4	5	6	7	8	9	10	11	12	13
	°C												
Zero Row	17.5	16.6	19.6	20.1	19.1	19.5	20.0	16.6	18.7	12.8	13.7	16.7	9.6
One Row	17.3	16.3	19.0	19.8	18.5	18.9	19.6	16.2	19.2	12.4	13.4	16.4	9.5
Two Row	17.9	16.7	19.4	20.1	18.8	19.3	20.2	16.8	19.7	12.8	13.8	16.8	10.1

*From June 25, 1982.

Comparison of the rate of development in both years indicated that the rate of development in 1981 was accelerated compared to 1982 (Table 7). Higher ambient air temperatures in 1981 compared to 1982 were responsible for the quicker development in 1981.

Plant Height

Soybean plant heights measured in 1981 and 1982 at different stages of growth showed non-significant differences between treatments (Tables 10 and 11). However, the two row windbreak treatments showed a non-significant reduction in plant height with time compared to zero and one row windbreak treatments in 1981, whereas in 1982, plants in the one and two row windbreak treatments grew non-significantly taller compared to plants in the zero windbreak treatment.

These results are in contrast to previous studies on effect of shelter on soybean growth reported in the literature, which indicated that soybeans grew significantly taller in response to shelter induced by temporary windbreaks (Sturrock 1970a) annual crop windbreaks (Radke and Burrows 1970) and perennial windbreaks (Ogbuehi and Brandle 1982).

The soybeans grew to a maximum height of about 95 cm in 1981 and 80 cm in 1982. The differences in previous soil management practices and growing season temperatures were responsible for this difference. The experiment in 1981 was situated on summer fallow, whereas in 1982, it was on barley stubble. The growing season in 1982 was cooler compared to 1981.

Sunflower height measurements (Figures 2 and 3) indicated that the summer fallow promoted early vigorous vegetative growth of sunflowers in 1981 compared to the barley stubble condition in 1982. Vigorous vegetative growth produced less permeable windbreaks in 1981 than in 1982. Windbreaks with low permeability promoted turbulence and hence increased the stress

TABLE 10. The effect of zero, one, and two row windbreak treatments on plant height measured at four dates in 1981.

	Plant Height			
Treatment	July 13	July 23	August 7	August 19
	cm			
Zero Row	25.5	45.1	75.9	95.2
One Row	25.9	45.5	77.1	95.5
Two Row	25.4	44.3	75.6	92.7
CV %	3.01	3.27	2.15	1.81

TABLE 11. The effect of zero, one, and two row windbreak treatments on plant height measured at three dates in 1982.

Treatment	Plant Height July 19	 August 6	 August 27
		cm	
Zero Row	26.4	59.6	75.3
One Row	28.4	64.9	80.4
Two Row	26.7	64.7	81.5
CV %	8.95	6.74	5.82

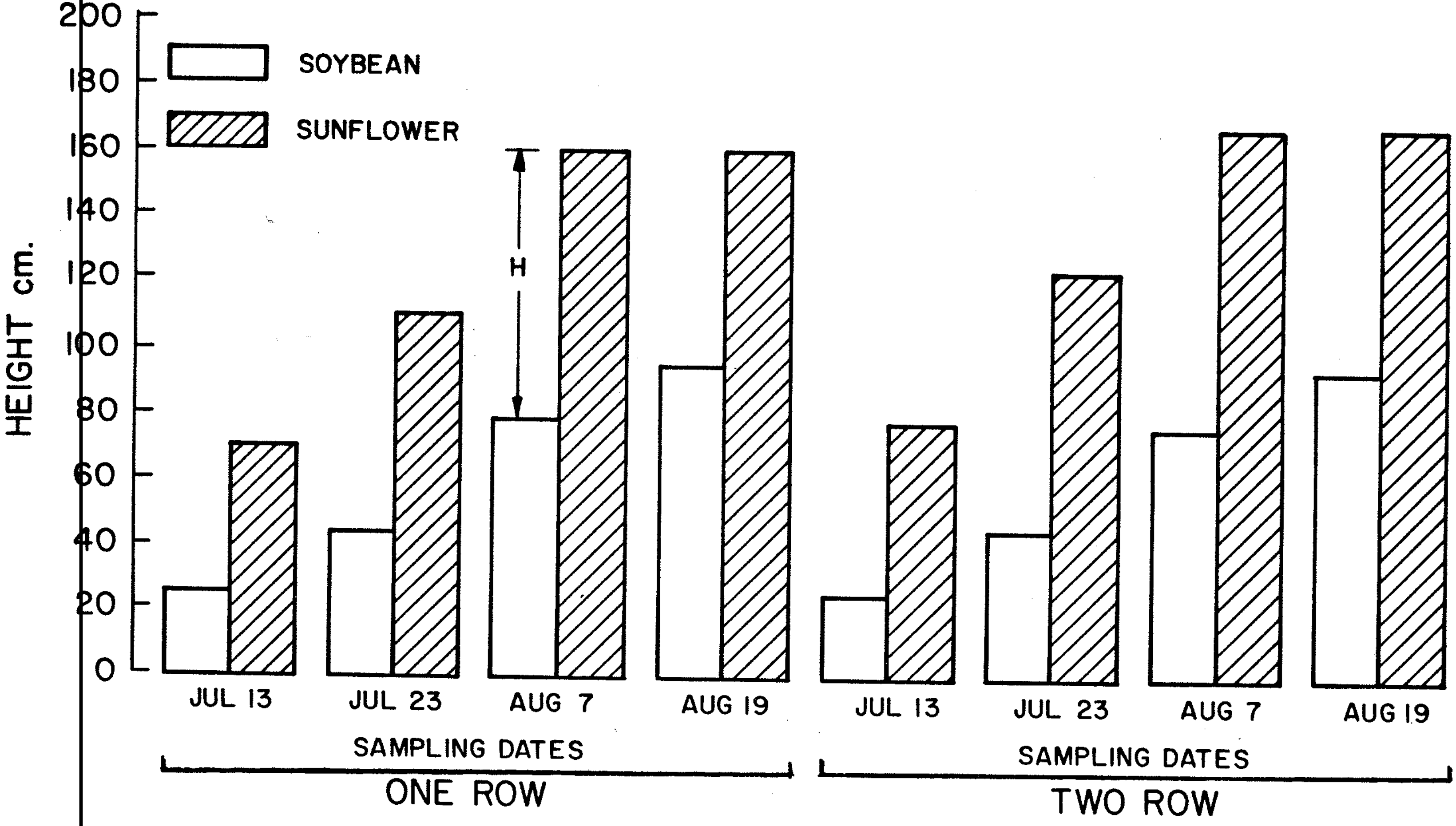

Figure 2. Height of soybeans, sunflowers, and effective windbreak height (H) at four dates of measurement for one and two row windbreak treatments in 1981.

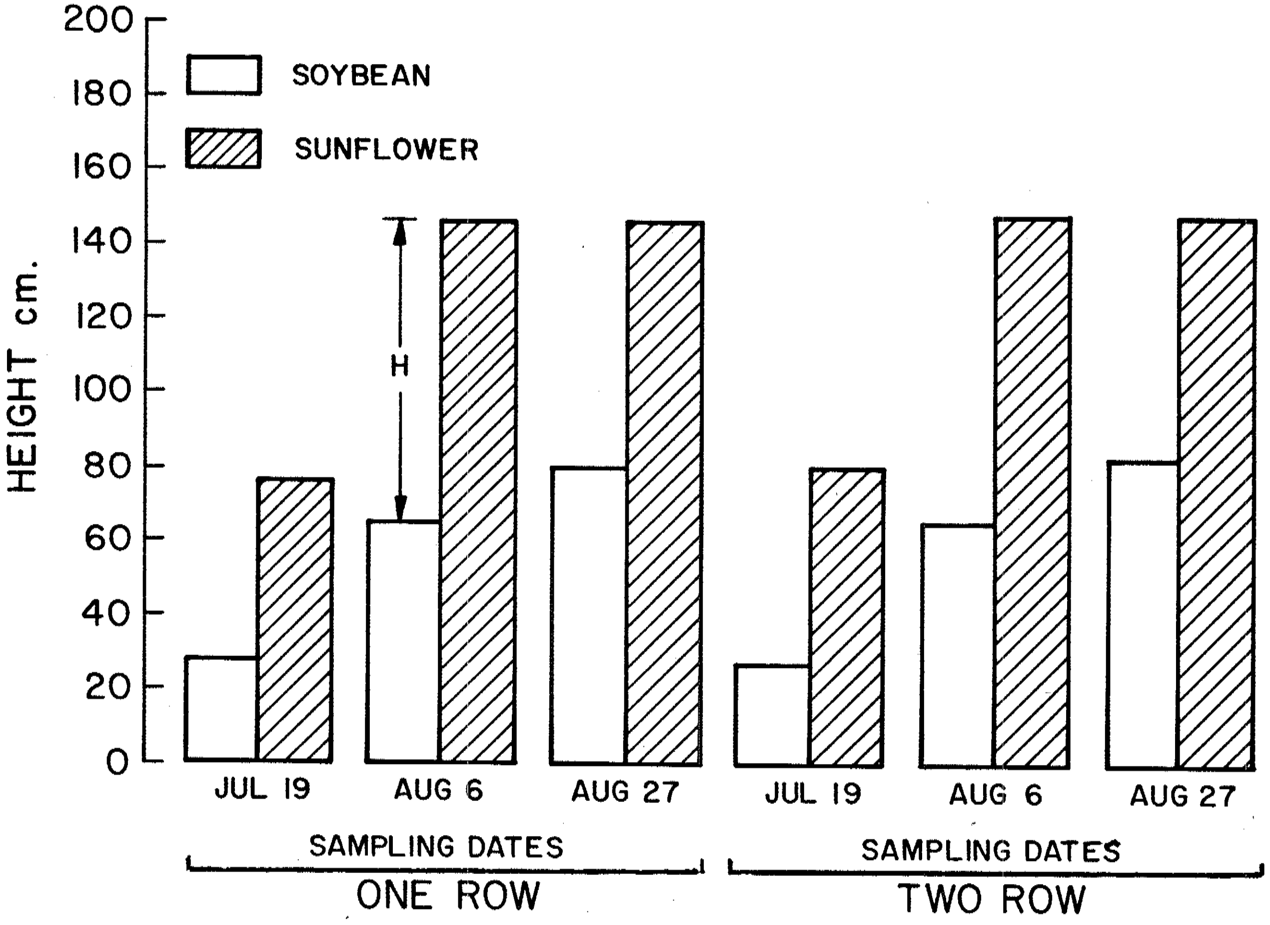

Figure 3. Height of soybeans, sunflowers, and effective windbreak height (H) at three dates of measurement for one and two row windbreak treatments in 1982.

condition on sheltered soybeans in 1981.

The area of sheltered zone increased with the advance of growth stage for both sunflowers and soybeans and reached a maximum when the maximum effective windbreak heights of approximately 82 and 91 cm in 1981 and 81 and 83 cm in 1982 were reached for the one and two row windbreak treatments, respectively (Figures 2 and 3). In both years, the maximum effective windbreak heights coincided with the period of seed formation (stage R_5). The effective windbreak heights decreased, after reaching a maximum to 64 and 74 cm in 1981 and 65 and 66 cm in 1982 for the one and two row windbreak treatments and remained constant thereafter.

Based on the assumption that the annual windbreaks modify microclimate favourably up to 12 H, sunflowers produced a maximum sheltered zone of 9 to 10 m and a constant sheltered zone of 7 to 8 m in both years. The decrease of sheltered area after reaching a maximum was due to the continued growth of the indeterminate soybean variety, McCall. Since the sunflowers did not reach the assumed effective windbreak height of 120 cm, the windbreaks never provided full shelter to the whole windbreak treatment plots.

Leaf Area

Leaf area, measured twice during the growing period in 1981 and reported as leaf area index, showed no significant differences between treatments (Table 12). In 1982, leaf area index, measured between the beginning of podding and the full pod stage, did not show significant differences between treatments. But leaf area index of the two row windbreak treatment measured between the beginning of the seed fill and the full seed stage differed significantly from the zero and one row windbreak treatments (Table 13).

These results are in contrast with the literature where significant leaf area increases of sheltered soybeans over unsheltered ones were reported

TABLE 12. The effect of zero, one, and two row windbreak treatments on leaf area index measured at two dates in 1981.

	Leaf Area Index	
Treatment	July 9	July 30
Zero Row	0.64	3.92
One Row	0.66	3.95
Two Row	0.59	3.62
CV %	10.96	7.71

TABLE 13. The effect of zero, one, and two row windbreak treatments on leaf area index measured at two dates in 1982.

	Leaf Area Index	
Treatment	July 30	August 17
Zero Row	2.12 a*	3.74 a
One Row	2.32 a	3.77 a
Two Row	2.34 a	4.26 b
CV %	10.30	6.48

*Means within columns followed by the same letter are not significantly different at P = 0.05 (Duncan's Multiple Range Test).

by Sturrock (1970a), Radke and Burrows (1970), Radke and Hagstrom (1973), Frank _et_ _al_. (1974), and Ogbuehi and Brandle (1982).

The second leaf area measurement in 1981, and the first leaf area measurement in 1982, determined between the beginning of podding and the full pod stage, showed no significant differences between treatments. Windbreaks during this period did not reach the maximum effective windbreak height. This was one of the probable reasons for the non-significant difference in leaf area index measured during this period.

In 1982, the second leaf area measurement was determined between the beginning of seed fill and the full seed stage. Windbreaks during this period had reached maximum effective windbreak height and sheltered a major portion of the plots and hence produced a significant difference in leaf area index between the two row windbreak treatment and the zero and one row windbreak treatments.

The leaf area index measured between the beginning of podding and the full pod stage showed that the leaf area index in 1981 was higher than 1982 for all treatments. The most probable reasons for this were the differences in previous soil management practices and growing season temperature.

The final leaf area depends on the number of leaves produced and the leaf area of each leaf. The leaf area of each leaf depends on cell division and cell enlargement.

Johnson _et_ _al_. (1960) reported that in soybeans all nodes are completely differentiated in 4 to 5 weeks after planting. Because the windbreaks produced full shelter effect 10 to 11 weeks after planting, the windbreak modified microclimate did not influence the differentiation of nodes and hence the number of leaves produced.

Gregory (1956) and Milthrope (1956) reported that temperature affects leaf area through its effects more on cell division than on leaf enlargement. The mean air temperature differences among zero, one, and two row windbreak treatments were very small in 1981, resulting in non-significant differences in leaf area among treatments. In 1982, the mean air temperature of the two row windbreak treatment was consistently higher than the one row windbreak treatment and was one probable cause for the significant increase in leaf area index seen for the two row windbreak treatment. Ciha and Brun (1975) also reported that leaf area of soybean increases as temperature increases in the 18 to 30° C range.

Water stress also causes reduction in leaf area in soybeans (Ciha and Brun 1975). Windbreaks in 1981 did not ameliorate stress conditions or the unsheltered environment did not induce stress conditions and therefore the windbreaks did not produce favourable effects on leaf area development. However, the two row windbreak treatment non-significantly reduced leaf area due to stress conditions produced by low permeability windbreaks.

Top Dry Weight

Top dry weights determined at different stages during the growing period were not significantly different among treatments in either 1981 or 1982 (Tables 14 and 15).

In 1981, the final top dry weight determined at the full seed stage showed that the zero windbreak treatment produced non-significantly higher dry weight than the one and two row windbreak treatments. But in 1982, one and two row windbreak treatments produced non-significantly higher top dry weight when compared to the zero windbreak treatment. Frank *et al*. (1974) also reported non-significant differences in top dry weight between sheltered and unsheltered dry land grown soybeans.

TABLE 14. The effect of zero, one, and two row windbreak treatments on top dry weight determined at three dates in 1981.

Treatment	Top Dry Weight July 8	 July 31	 September 2
	g/m row		
Zero Row	25.0	159.9	523.4
One Row	25.8	163.9	487.8
Two Row	24.3	157.1	487.3
CV %	9.91	8.81	5.17

TABLE 15. The effect of zero, one, and two row windbreak treatments on top dry weight determined at four dates in 1982.

Treatment	Top Dry Weight			
	July 13	July 30	August 17	September 3
	g/m row			
Zero Row	35.4	115.7	275.4	421.5
One Row	36.9	118.1	276.3	443.2
Two Row	37.9	122.9	288.2	440.9
CV %	16.52	11.01	9.34	6.28

Dense sunflower windbreaks in 1981 promoted stress conditions on the soybeans as a consequence of the increased turbulence, causing the sheltered plants to have a non-significantly lower top dry weight compared to unsheltered soybean plants. Radke and Hagstrom (1974) studied the turbulence produced by different windbreaks and showed sunflower windbreaks promoted turbulence compared to corn windbreaks.

Sheltered windbreak treatments had higher weekly mean canopy air temperatures in 1981. Higher canopy temperatures are indicative of stress under dry land conditions. Frank _et al_. (1974) reported higher canopy temperatures for non-irrigated sheltered soybeans and showed that higher canopy temperatures indicated stress conditions on the soybeans. In the experiment reported here, permeable sunflower windbreaks in 1982 did not produce stress conditions to sheltered soybeans and hence produced a non-significant increase in top dry weight compared to unsheltered treatments.

Radke and Burrows (1970), Radke and Hagstrom (1973), Frank _et al_. (1974), and Ogbuehi and Brandle (1982) reported that improved plant water relations of sheltered soybeans was responsible for improved vegetative growth. In the investigation reported here, vegetative growth parameters did not show significant improvement with windbreaks and, therefore, the windbreaks probably did not influence the plant water relations of soybeans.

It is possible that the unsheltered microclimate at Portage la Prairie did not induce moisture stress on soybeans during the years of investigation and, therefore, could not influence the plant water relations of soybeans. Brown and Rosenberg (1975) reported that in the absence of hot dry desiccating winds, annual windbreaks did not produce favourable effects on crop growth, but sometimes produced unfavourable effects.

The other possible factor is that the annual windbreaks did not produce full shelter early enough in the growing season and therefore did not affect the vegetative growth.

Another factor is that the soybean cultivar used in this investigation may be non-responsive to windbreak induced microclimate. Sturrock (1970b) and Radke and Hagstrom (1976) reported soybean cultivars differed in their response to windbreaks. Skidmore et al. (1974) reported that cultivars of winter wheat responded differently to shelter by producing differing plant water relations.

Pod Number Per Plant

The zero row windbreak treatment produced a significantly higher number of pods per plant compared to one and two row windbreak treatments in 1981 (Table 16). In 1982, the number of pods per plant did not differ significantly among the zero, one, and two row windbreak treatments. However, the zero windbreak treatment had non-significantly higher pod number compared to one and two row windbreak treatments (Table 16).

In soybeans, moisture stress during flowering increases abortion of flowers and young pods (Doss et al. 1974). In 1981, turbulence produced by dense windbreaks caused moisture stress and hence abortion of flowers and pods. This was the probable cause of the significant reduction in pod number in plants grown under one and two row windbreak treatments in 1981, whereas in 1982, less dense windbreaks did not promote turbulence and hence did not affect significantly the number of pods produced per plant.

All treatments had a higher number of pods per plant in 1981 compared to 1982. The differences in previous soil management practices and growing season temperatures were responsible for the difference in pod number per plant between the two years.

TABLE 16. The effect of zero, one, and two row windbreak treatments on the number of pods per plant in 1981 and 1982.

	Pod Number per Plant	
Treatment	1981	1982
Zero Row	37.8 a[*]	32.9 a
One Row	35.1 b	31.2 a
Two Row	34.2 b	31.0 a
CV %	3.21	11.24

[*] Means within columns followed by the same letter are not significantly different at P = 0.05 (Duncan's Multiple Range Test).

Seed Yield

In 1981, the zero and one row windbreak treatments produced significantly higher seed yield compared to the two row windbreak treatment, whereas in 1982, there was no significant difference in yield between the treatments (Table 17).

Similar trends were reported for dry land grown soybeans by Frank et al. (1974). They reported a significant yield increase of unsheltered soybeans over sheltered ones in one year and non-significant yield difference in another year.

In 1981, stress conditions produced by the low permeability two row windbreak treatment significantly reduced seed yield through significant reduction of pod number per plant. But significant reduction of pod number due to stress in the one row windbreak treatment did not result in significant reduction in yield. Higher canopy air temperatures also seemed to indicate occurance of moisture stress in these treatments.

The other probable reason may be reduced photosynthesis due to reduction of wind speed below optimum level by the low permeability two row windbreak treatment. Lemon (1970) reported that reduction of wind speed below optimum under field conditions impaired carbon dioxide supply to leaves and hence affected photosynthesis.

In 1982, the one row windbreak treatment produced non-significantly higher seed yield compared to the zero and two row windbreak treatments. Higher canopy temperatures of the zero and two row windbreak treatments indicated moisture stress conditions, and seemed to be responsible for low yield in these treatments.

Figures 4 and 5 show the yield of 26 rows of soybeans in 1981 and 1982. Rows 1 and 26 from the one and two row windbreak treatments showed very low

TABLE 17. The effect of zero, one, and two row windbreak treatments on seed yield in 1981 and 1982.

Treatment	Seed Yield 1981		Seed Yield 1982	
	kg/ha			
Zero Row	2635	a*	1631	a
One Row	2579	a	1705	a
Two Row	2510	b	1597	a
CV %	1.8		13.2	

*Means within columns followed by the same letter are not significantly different at P = 0.05 (Duncan's Multiple Range Test).

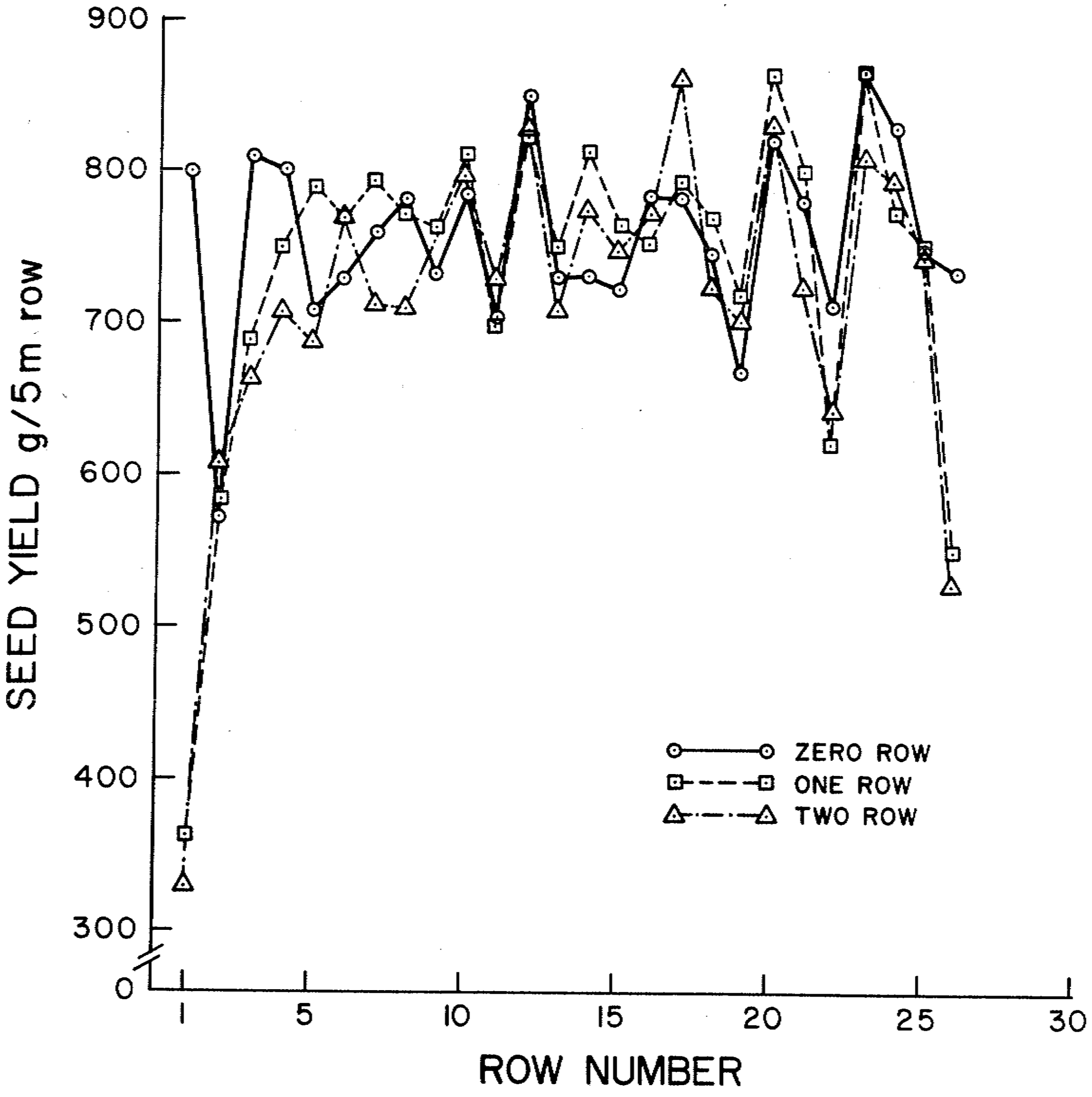

Figure 4. Seed yield of 26 x 5 m row samples for zero, one, and two row windbreak treatments in 1981.

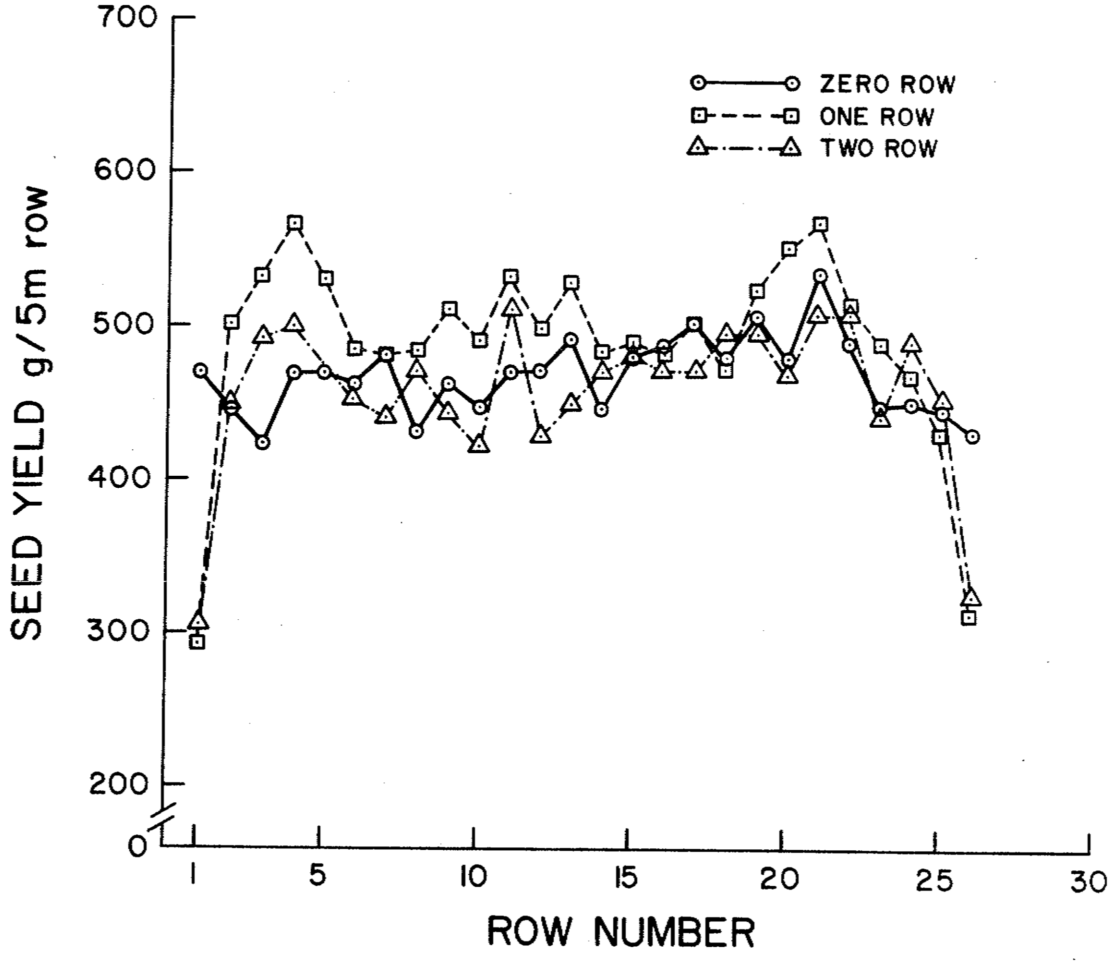

Figure 5. Seed yield of 26 x 5 m row samples for zero, one, and two row windbreak treatments in 1982.

seed yield compared to the zero row windbreak treatment. This was due to shading and root competition by the adjacent sunflower windbreaks. Yield from other rows varied, but the one row windbreak treatment consistently produced higher yield per row than the zero and two row windbreak treatments. Radke and Burrows (1970) reported that the yield of soybeans nearest to the corn windbreaks showed no yield advantage but other rows from sheltered plots produced higher yield over unsheltered ones. They also reported that the yield loss of soybeans from rows adjacent to corn windbreaks was due to light and root competition.

Yield reduction from rows 1 and 26 of the one and two row windbreak treatments were higher than the yield gain from the other rows of the respective windbreak treatments and hence total plot yield of the two row windbreak treatment was significantly lower and plot yield of the one row windbreak treatment was non-significantly lower than the zero row windbreak treatment in 1981.

In 1982, the yield reduction from rows 1 and 26 of the one row windbreak treatment was less than the yield gain of other rows and, therefore, the overall yield was non-significantly higher for the one row windbreak treatment than for other treatments.

Both in 1981 and 1982, yield from rows 1 and 2, and 25 and 26 from the one and two row windbreak treatments, differed significantly from rows 5 and 6, 12 and 13, and 20 and 21 (Table 18). In 1981, yield from rows 1 and 2 was significantly lower than for rows 25 and 26. In 1981, seed yield from rows 5 and 6, 12 and 13, and 20 and 21 did not differ significantly. But in 1982, yield from rows 20 and 21 differed significantly from rows 5 and 6 and 12 and 13 for the one row windbreak treatment and from rows 12 and 13 for the two row windbreak treatment.

Seed yield was higher in 1981 compared to 1982. Lower than normal temperatures during the growing season and occurrence of a killing frost caused low seed yield in 1982.

TABLE 18. Seed yield of five sub-plots within a plot for zero, one, and two row windbreak treatments in 1981 and 1982.

	Zero Row		One Row		Two Row	
Sub-plot	1981	1982	1981	1982	1981	1982
	kg/ha					
Rows 1 and 2	2505 b*	1667 bc	1726 c	1458 c	1716 c	1387 c
Rows 5 and 6	2640 b	1705 b	2831 a	1851 b	2663 a	1683 ab
Rows 12 and 13	2886 a	1741 ab	2859 a	1871 b	2794 a	1607 b
Rows 20 and 21	2908 a	1851 a	3025 a	2041 a	2838 a	1790 a
Rows 25 and 26	2695 ab	1613 c	2386 b	1369 c	2326 b	1423 c

*Means within columns followed by the same letter are not significantly different at P = 0.05 (Duncan's Multiple Range Test).

Seed Weight

Seed weight determined as weight of 1000 seeds showed that the two row windbreak treatment had significantly higher seed weight than the zero row windbreak treatment in 1981. In 1982, the seed weight did not differ significantly between treatments. Although there was no significant difference, the two row windbreak treatment had non-significantly higher seed weight compared to the zero and one row windbreak treatments (Table 19).

Sturrock (1970a) reported significantly higher bean weight for sheltered soybeans. Frank *et al.* (1974) reported significantly higher seed weight of irrigated sheltered soybeans but non-significant differences in bean weight between sheltered and unsheltered dry land grown soybeans.

The significant reduction of pods in the two row windbreak treatment in 1981 caused production of significantly larger seeds but significant reduction of pods in the one row windbreak treatment did not result in significantly larger seeds. Higher maximum temperature in the two row windbreak treatment also would have enhanced larger seed size.

The differences in previous soil management practices, growing season temperatures, and killing frost that occurred before the onset of maturity in 1982 caused production of smaller seeds in 1982.

Seed Quality

In 1981, the oil content of the two row windbreak treatment was significantly higher than the zero row windbreak treatment. But in 1982, there was no significant difference in oil content between treatments (Table 20).

Oil content of soybean seeds is influenced by temperature, higher oil content correlating with higher growing temperatures (Whigham and Minor 1978). The two row windbreak treatment in 1981 had higher maximum temperature during the seed filling stage and would have influenced the oil content of seeds.

TABLE 19. The effect of zero, one, and two row windbreak treatments on seed weight in 1981 and 1982.

	Seed Weight	
Treatment	1981	1982
	g/1000 seed	
Zero Row	151.5 a*	118.6 a
One Row	155.5 ab	118.6 a
Two Row	159.8 b	121.7 a
CV %	2.39	5.59

*Means within column followed by same letter are not significantly different at P = 0.05 (Duncan's Multiple Range Test).

TABLE 20. The effect of zero, one, and two row windbreak treatments on oil and protein percentage of seeds in 1981 and 1982.

	Oil		Protein	
Treatment	1981	1982	1981	1982
		%		
Zero Row	19.7 a	20.6 a	41.9 a	36.4 a
One Row	19.9 ab	20.7 a	41.5 ab	35.4 a
Two Row	20.2 b	19.8 a	40.8 b	38.0 a
CV %	1.23	3.31	1.56	5.77

[*] Means within columns followed by the same letter are not significantly different at P = 0.05 (Duncan's Multiple Range Test).

But in 1982, the temperature differences may not have been adequate to influence the oil content of seeds.

Protein content of seed is not influenced by temperature. But the inverse relationship between oil and protein content caused significantly lower protein content in soybean seeds produced under the two row windbreak treatment compared to the zero row windbreak treatment in 1981. But in 1982, the protein content among treatments did not differ significantly (Table 20). Occurrence of a killing frost at the onset of maturity was one reason for lower protein content in 1982 compared to 1981.

Water Use

Water use of soybean plants was calculated from soil water determinations both in 1981 and 1982. Total water content of the 0 to 120 cm soil profile for the zero, one, and two row windbreak treatments for specified sampling dates are shown in Appendices 5 and 6. Water use between the period of July 13 to August 27 in 1981, and June 16 to August 30 in 1982, indicated that no significant differences occurred among zero, one, and two row windbreak treatments (Table 21). Soybean plants used an average of 2.73 mm of water per day during the period of observation in 1981 and 3.21 mm per day in 1982.

Similar non-significant water use patterns were reported between unsheltered soybeans and soybeans sheltered by temporary windbreaks (Radke and Burrows 1970) and perennial windbreaks (Ogbuehi and Brandle 1982).

In 1982, water use determined after the windbreaks had reached the maximum effective windbreak heights also indicated no significant difference among treatments (Table 22). But in 1981, zero and one row windbreak treatments differed significantly in water use.

The seasonal water use pattern indicated that the water use increased with progress of growth and then declined. In both years, the maximum water use coincided with the period of seed formation (Figures 6 and 7).

TABLE 21. Total water use between July 13 to August 27, 1981 and June 16 to August 30, 1982.

Treatment	Water Use	
	July 13-August 27, 1981	June 16-August 30, 1982
	cm	
Zero Row	12.3	24.4
One Row	12.5	24.8
Two Row	12.8	24.2
CV %	4.78	8.43

TABLE 22. Water use between August 4 to 14 in 1981 and August 4 to 20 in 1982.

Treatment	Water Use August 4-14, 1981	 August 4-20, 1982
	cm	
Zero Row	6.2 a*	5.7 a
One Row	7.4 b	4.7 a
Two Row	7.2 ab	6.2 a
CV %	7.61	21.42

*Means within columns followed by the same letter are not significantly different at P = 0.05 (Duncan's Multiple Range Test).

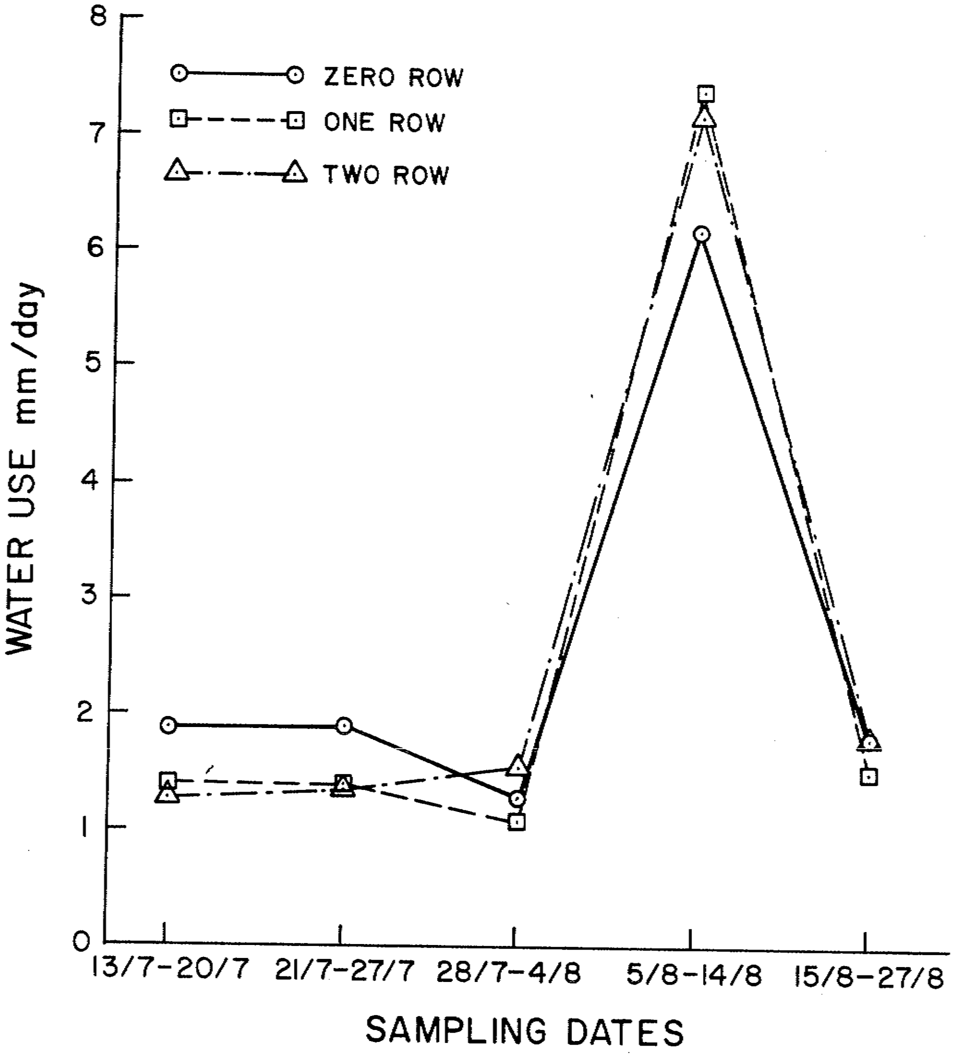

Figure 6. Seasonal water use by soybeans grown under zero, one, and two row windbreak treatments between specified sampling dates in 1981.

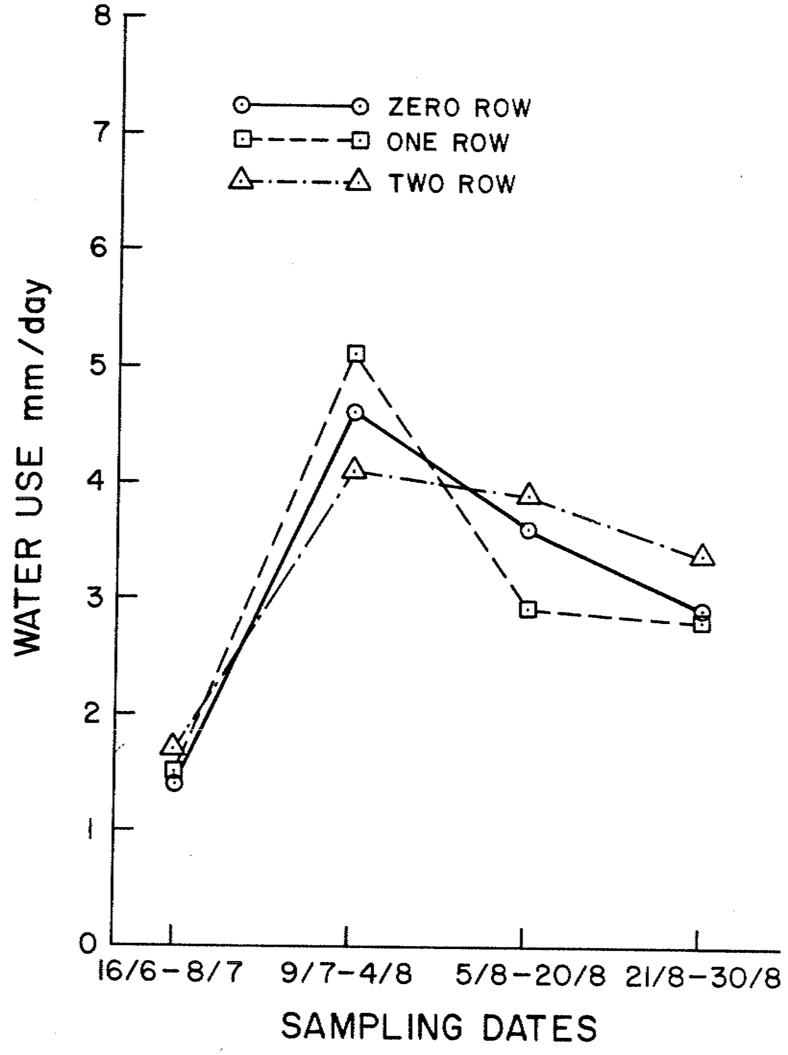

Figure 7. Seasonal water use by soybeans grown under zero, one, and two row windbreak treatments between specified sampling dates in 1982.

Canopy Air Temperature

Weekly mean canopy air temperatures derived from daily maximum, minimum, and mean temperatures recorded between rows 3 and 4, 12 and 13, and 22 and 23 from July 22, 1981 are reported in Figures 8, 9, and 10.

Temperatures recorded between rows 3 and 4 showed the one row windbreak treatment had the highest maximum temperature followed by the two and zero row windbreak treatments. Minimum temperatures did not vary between treatments. Mean temperatures followed a similar pattern to maximum temperatures.

Temperatures recorded between rows 12 and 13 showed that the two row windbreak treatment had the highest maximum temperature followed by the one and zero row windbreak treatments. Minimum temperatures did not vary between treatments. Mean temperatures followed a similar pattern to maximum temperatures.

Temperatures recorded between rows 22 and 23 showed that the zero row windbreak treatment had the highest maximum temperature followed by the one and two row windbreak treatments. Both minimum and mean temperatures showed little variation. The temperature difference among treatments was small compared to other locations.

Weekly mean canopy air temperatures derived similar to 1981 from daily maximum, minimum, and mean temperatures recorded between rows 8 and 9 and 18 and 19 from June 25, 1982 are shown in Figures 11 and 12. Temperatures monitored in both locations indicated that higher maximum temperatures occurred for zero and two row windbreak treatments compared to the one row windbreak treatment. Minimum and mean temperatures followed similar patterns.

Higher canopy temperatures under dry land condition indicated moisture stress in soybeans (Frank _et al_. 1974) and spring wheat (Frank _et al_. 1977b). Higher canopy air temperatures in the one and two row windbreak treatments compared

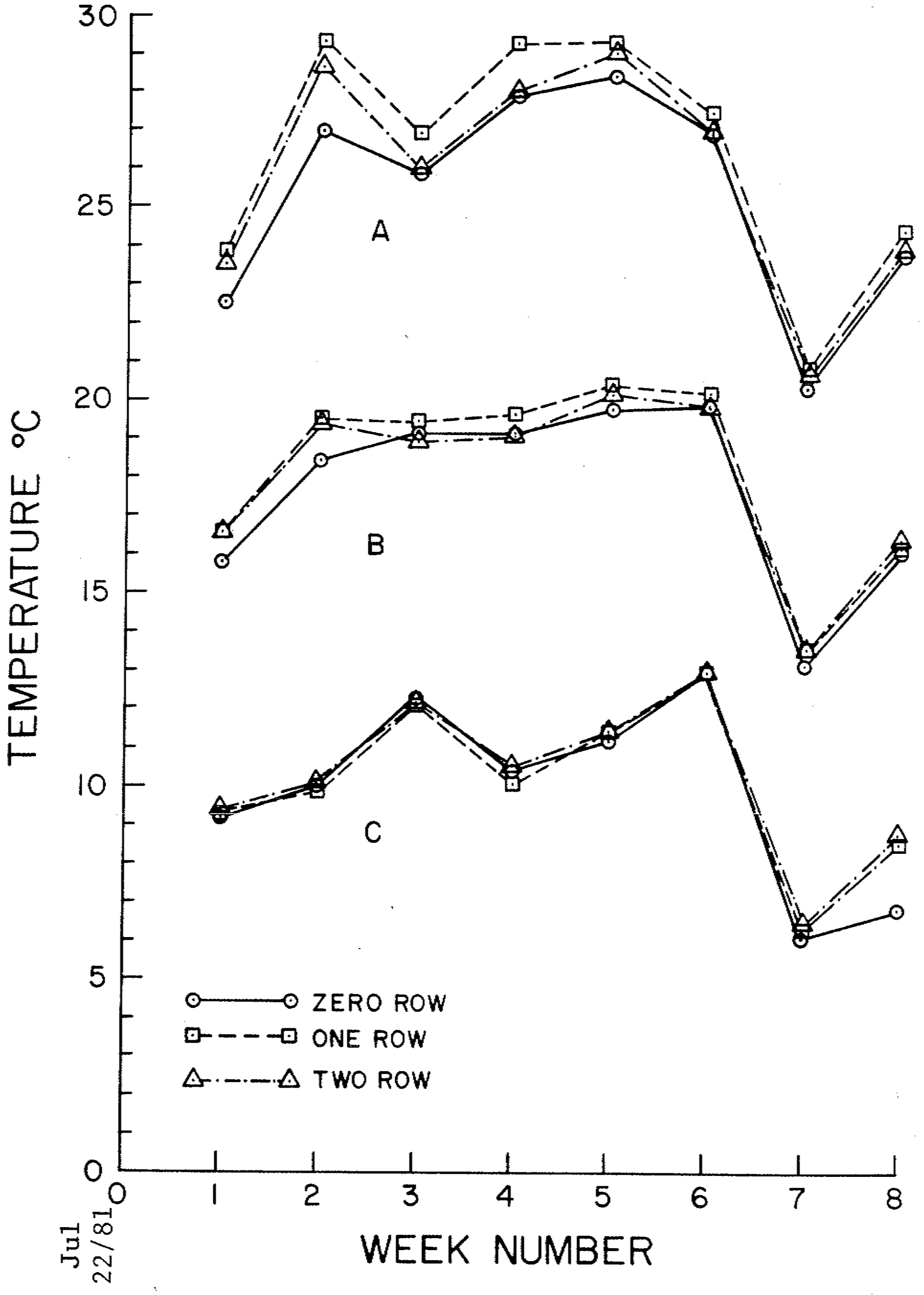

Figure 8. Weekly maximum (A), minimum (C), and mean (B) canopy air temperatures for zero, one, and two row windbreak treatments, recorded between rows 3 and 4 in 1981.

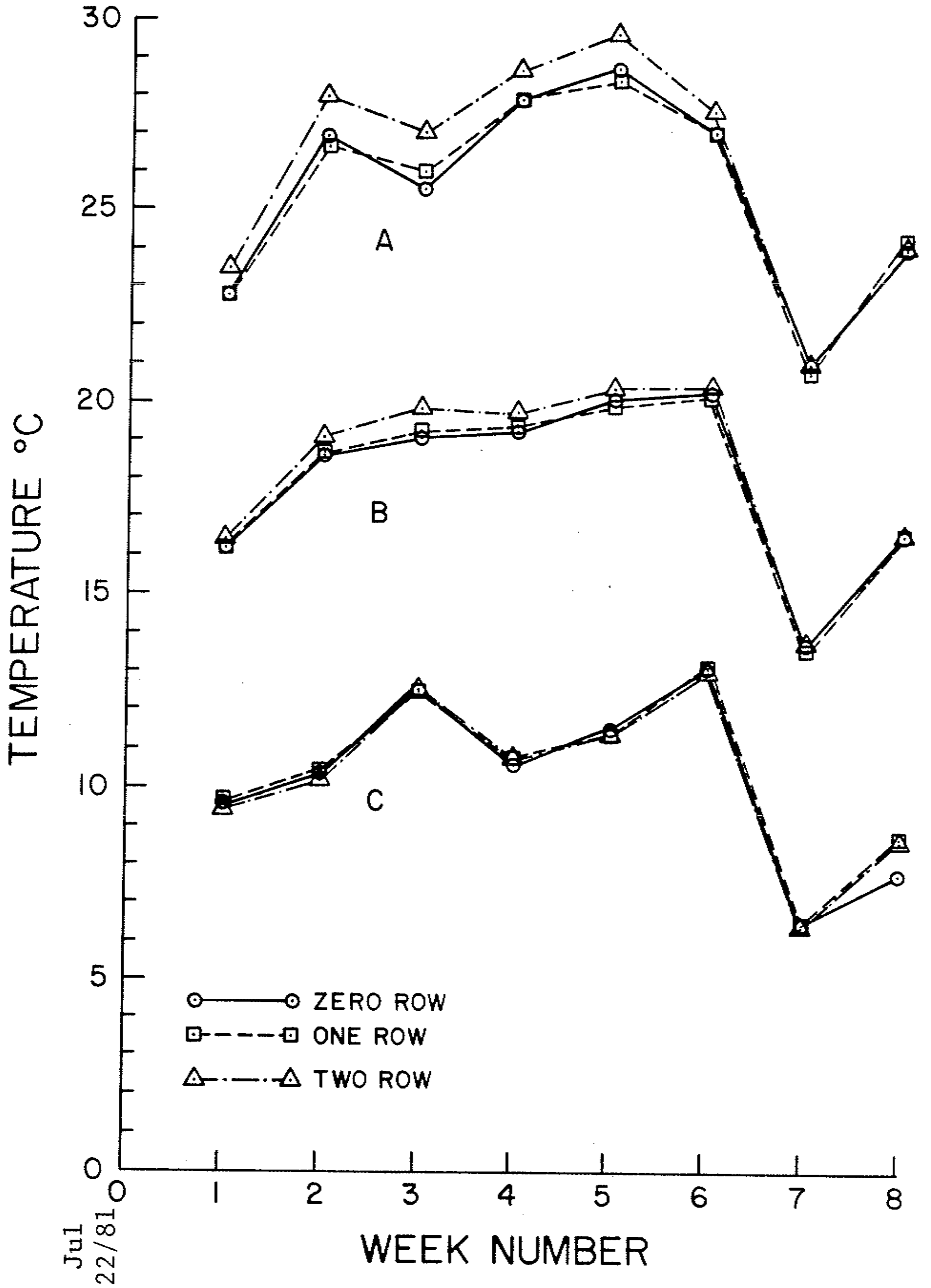

Figure 9. Weekly maximum (A), minimum (C), and mean (B) canopy air temperatures for zero, one, and two row windbreak treatments, recorded between rows 12 and 13 in 1981.

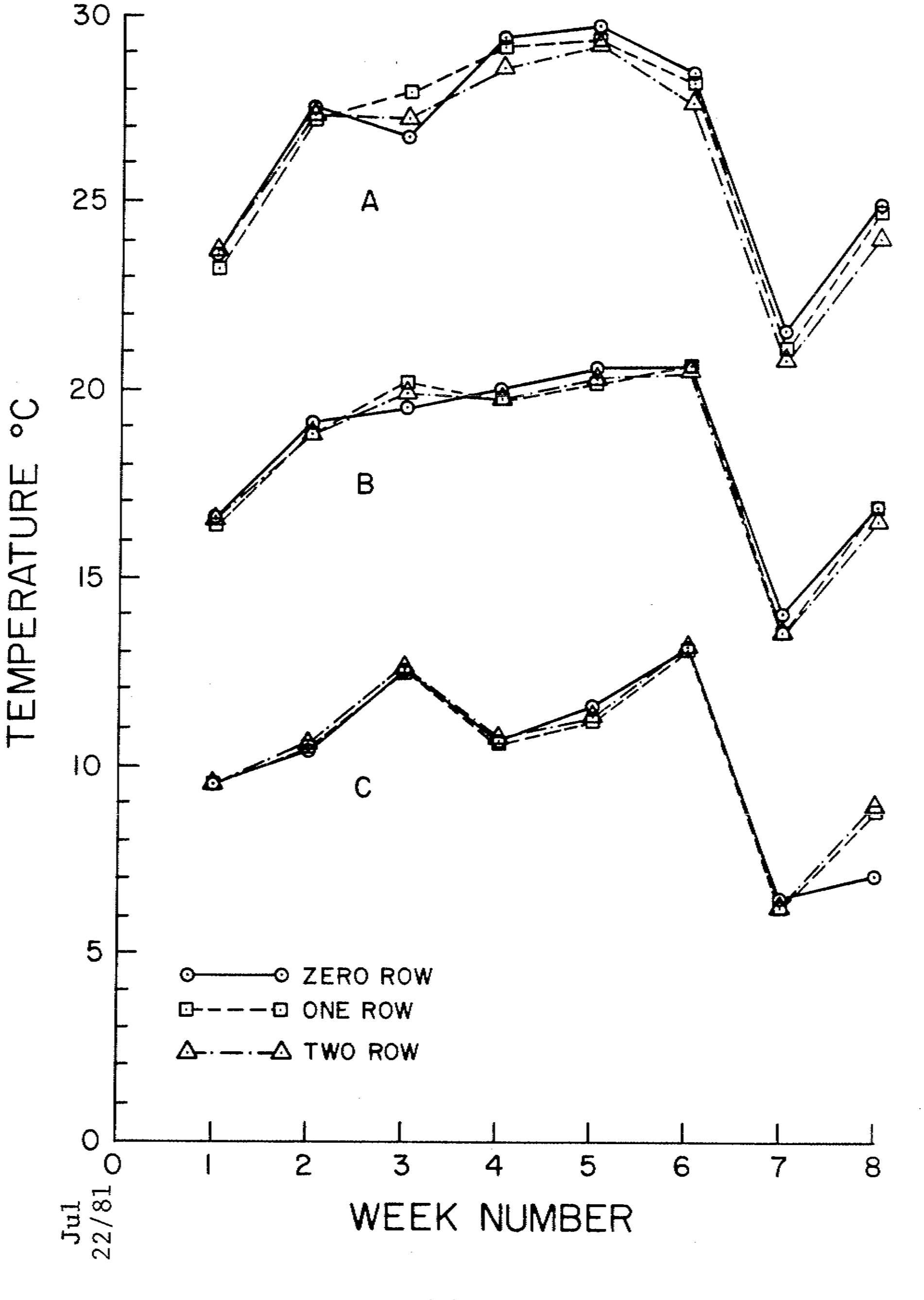

Figure 10. Weekly maximum (A), minimum (C), and mean (B) canopy air temperatures for zero, one, and two row windbreak treatments, recorded between rows 22 and 23 in 1981.

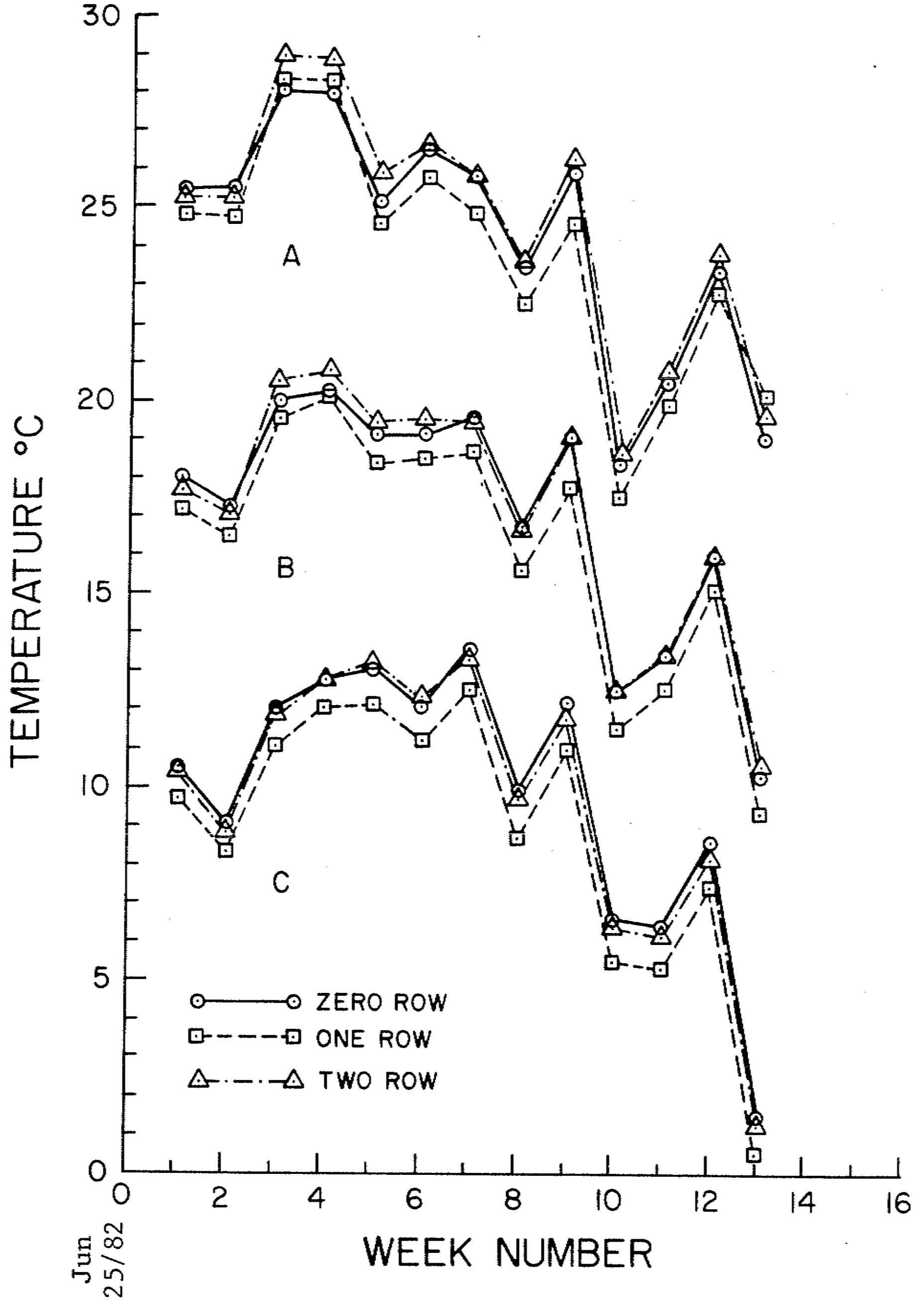

Figure 11. Weekly maximum (A), minimum (C), and mean (B) canopy air temperatures for zero, one and two row windbreak treatments, recorded between rows 8 and 9 in 1982.

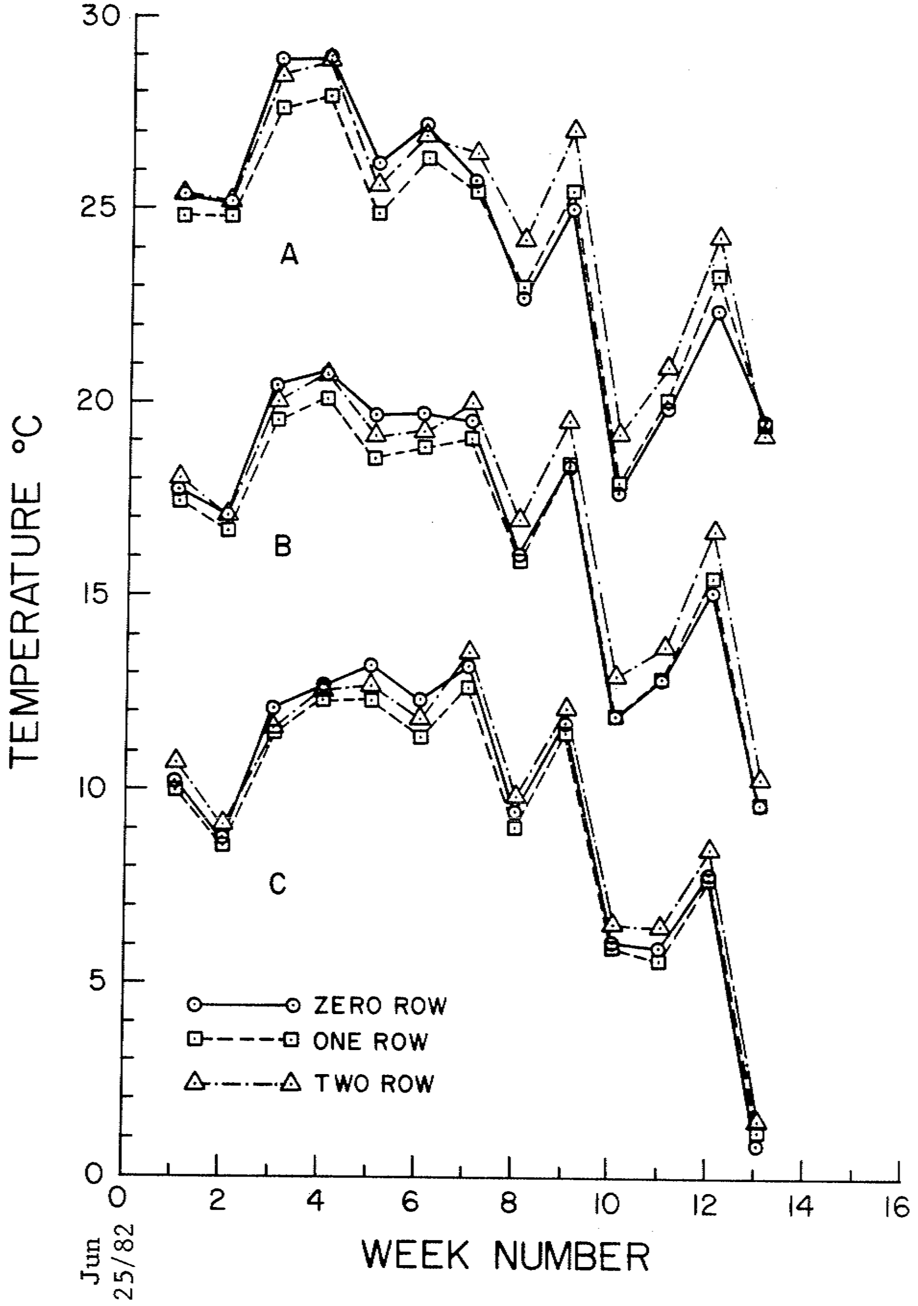

Figure 12. Weekly maximum (A), minimum (C), and mean (B) canopy air temperatures for zero, one, and two row windbreak treatments, recorded between rows 18 and 19 in 1982.

to the zero row windbreak treatment in 1981 seemed to indicate that these two treatments were under moisture stress. Turbulence caused by windbreaks of low permeability in 1981 seemed to be the cause for stress conditions in the one and two row windbreak treatments. Stress conditions seemed to be the probable cause for significantly fewer pods per plant in the one and two row windbreak treatments and significantly lower yield in the two row windbreak treatment.

In 1982, stress conditions in the zero and two row windbreak treatments did not produce significant differences among treatments in pod number per plant or yield.

High temperature in the range of 27° C increases the seed size of soybeans (Whigham and Minor 1978). Higher canopy air temperatures in the one and two row windbreak treatments seemed to be responsible for significant increase in seed size compared to the zero row windbreak treatment. A similar trend was observed in 1982, where higher temperatures in the two row windbreak treatment seemed to be responsible for a non-significant increase in seed weight.

Air Temperature

Weekly mean air temperatures derived from daily maximum, minimum, and mean temperatures recorded between rows 3 and 4, 12 and 13, and 22 and 23 in 1981 are reported in Figures 13, 14, and 15. Weekly mean temperatures recorded between rows 8 and 9, and 18 and 19 in 1982 are reported in Figures 16 and 17.

Temperature patterns indicated that both higher and lower temperatures occurred in the sheltered zone of the one and two windbreak treatments compared to the zero row windbreak treatment.

Occurrence of both higher and lower than normal temperatures in the sheltered zone was related to the wind reducing patterns in the sheltered zone

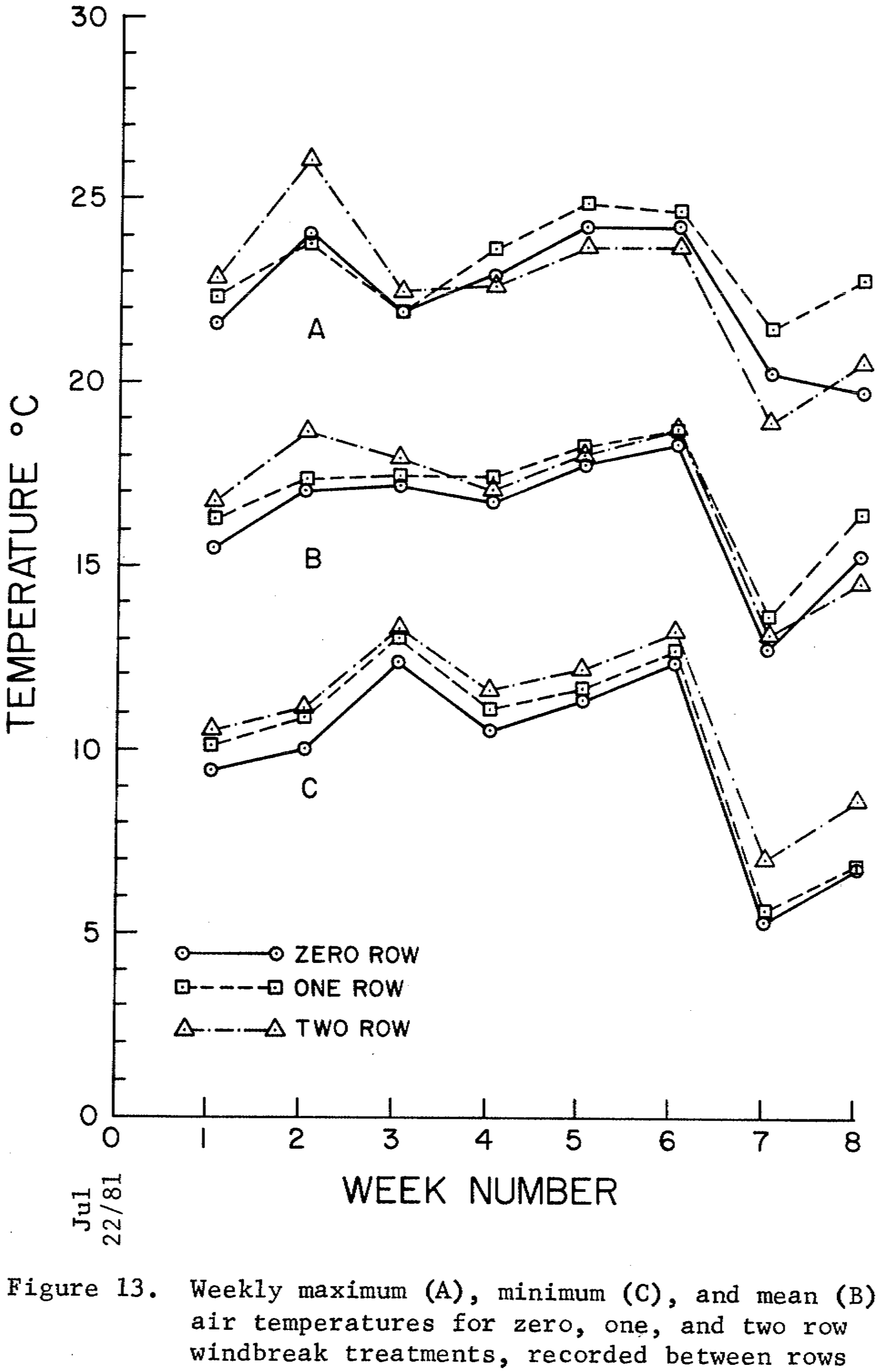

Figure 13. Weekly maximum (A), minimum (C), and mean (B) air temperatures for zero, one, and two row windbreak treatments, recorded between rows 3 and 4 in 1981.

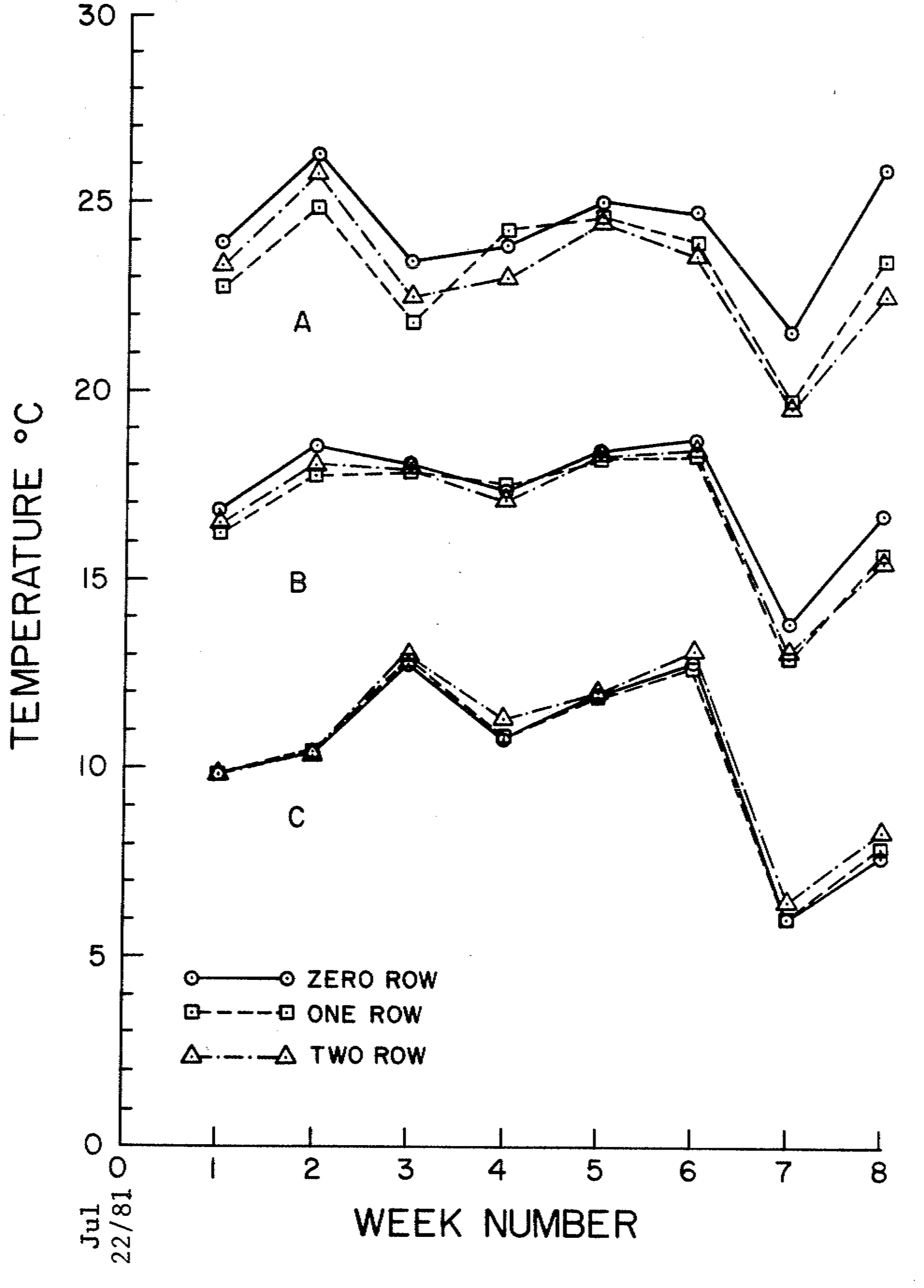

Figure 14. Weekly maximum (A), minimum (C), and mean (B) air temperatures for zero, one, and two row windbreak treatments, recorded between rows 12 and 13 in 1981.

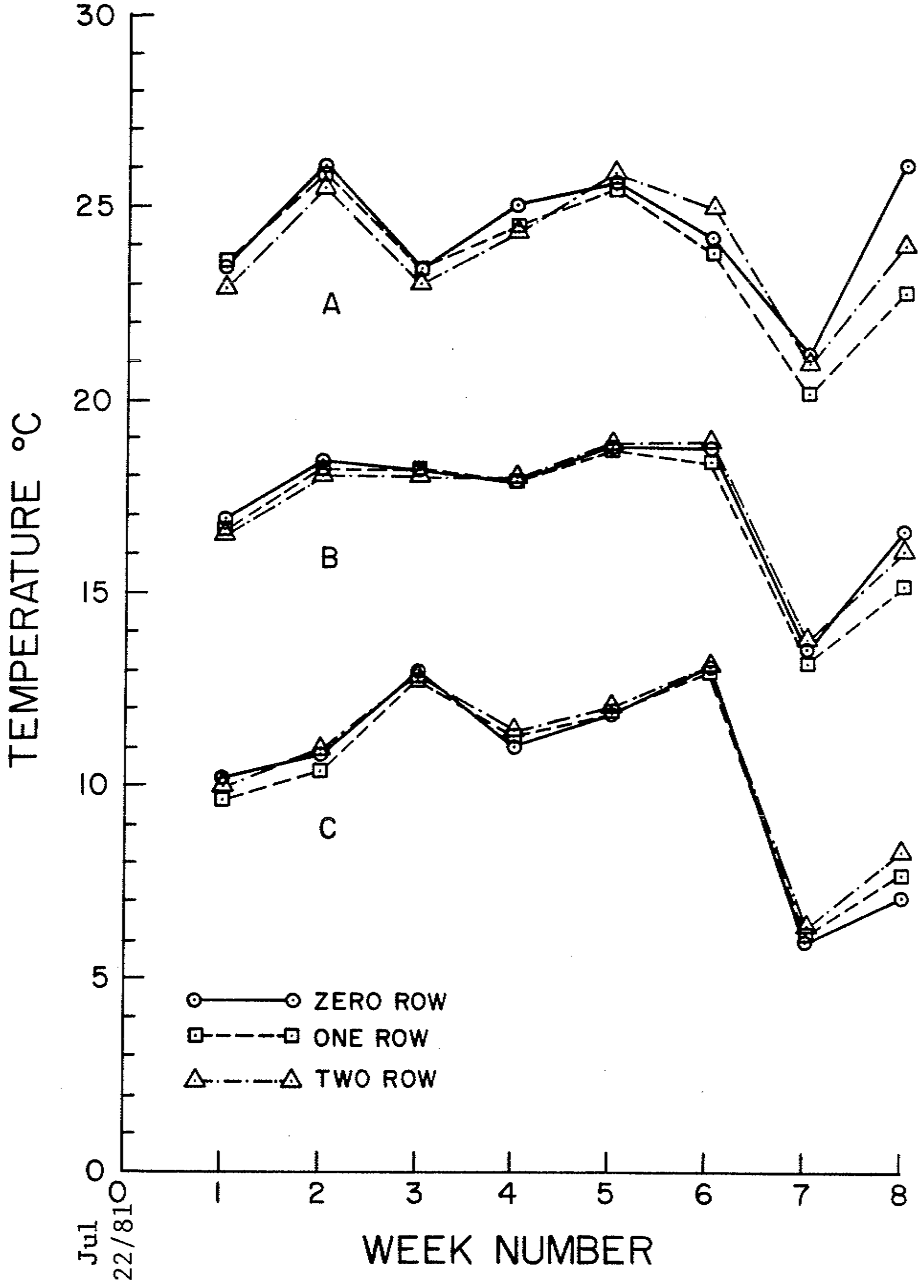

Figure 15. Weekly maximum (A), minimum (C), and mean (B) air temperatures for zero, one, and two row windbreak treatments, recorded between rows 22 and 23 in 1981.

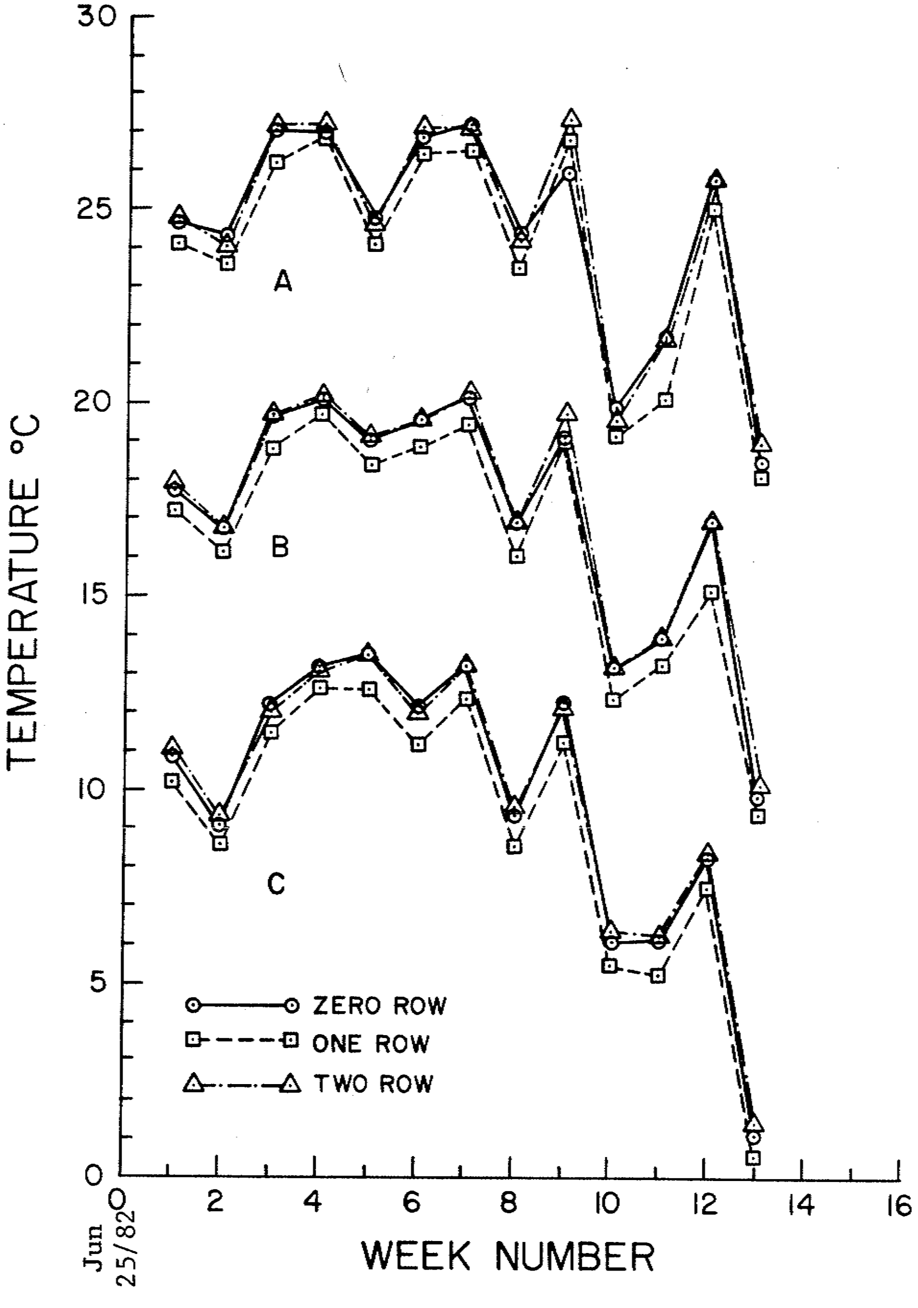

Figure 16. Weekly maximum (A), minimum (C), and mean (B) air temperatures for zero, one, and two row windbreak treatments, recorded between rows 8 and 9 in 1982.

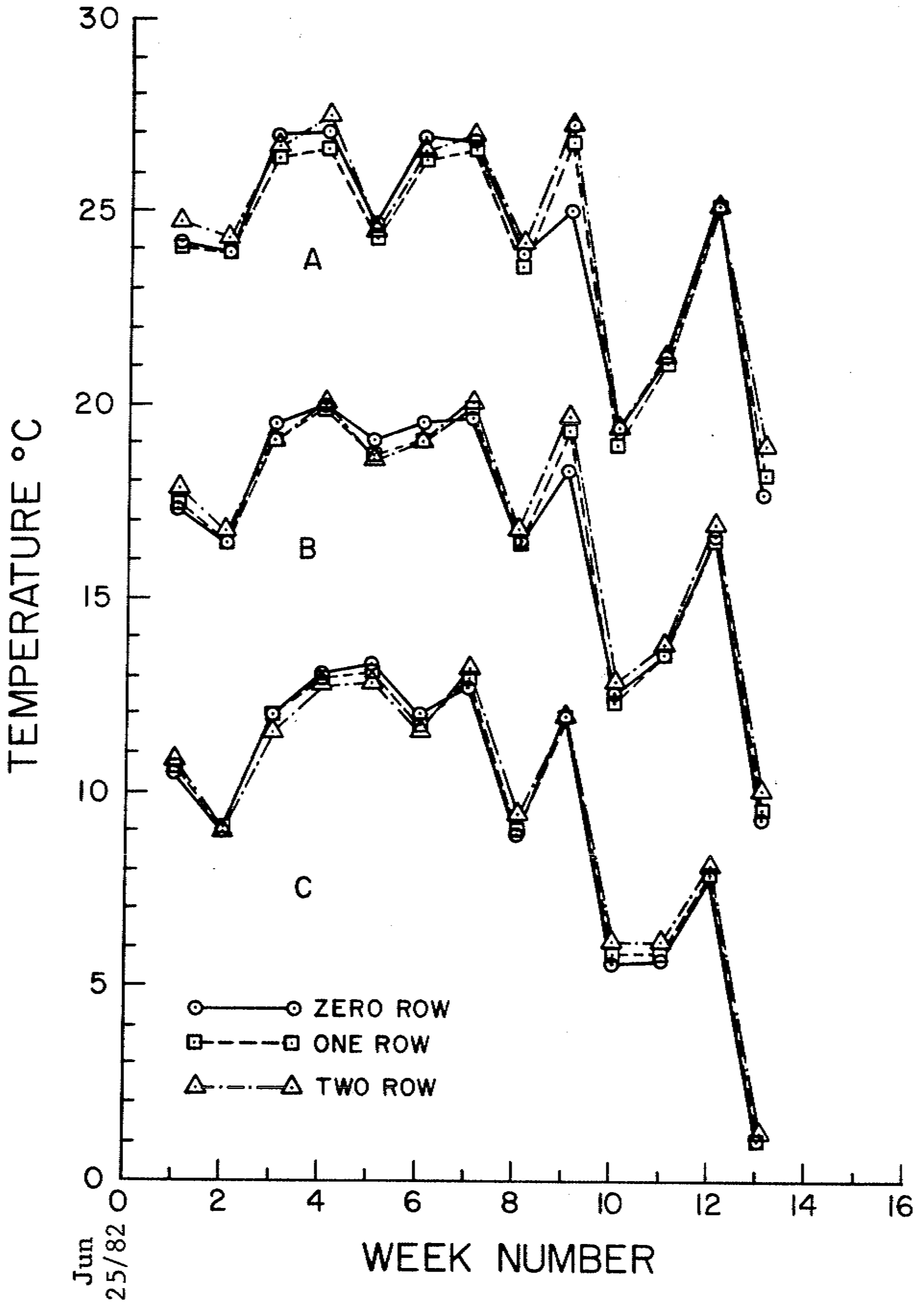

Figure 17. Weekly maximum (A), minimum (C), and mean (B) air temperatures for zero, one, and two row windbreak treatments, recorded between rows 18 and 19 in 1982.

by Woodruff et al. (1959) and Hagen and Skidmore (1971). In this study, occurrence of both higher and lower than normal temperatures in the sheltered zone of windbreak treatments seemed to correlate to the location where the temperatures were monitored. Comparison of the one and two row windbreak treatments seemed to indicate that windbreak permeability determined the occurrence of both higher and lower than normal temperatures at different locations in the sheltered zone.

East-West Oriented Windbreak Experiment

Phenological Development

Similar to north-south oriented windbreaks, east-west oriented windbreaks did not affect the rate of development as indicated by the number of days to reach a phenological growth stage in the 1982 growing season (Table 23).

Plant Height

Plant height measurements determined on July 19 and August 9 did not show any significant difference among treatments. But the plant height measured on August 23 showed that both the one and two row windbreak treatments grew significantly taller than the zero row windbreak treatment (Table 24).

The first measurement was taken before the achievement of maximum effective windbreak height and the second and third measurements were taken after the period of maximum effective windbreak height. The second measurement showed a non-significant increase in plant height, whereas the third measurement showed a significant increase in plant height.

Height measurements of soybeans and sunflowers indicated that maximum effective windbreak heights of approximately 80 and 86 cm were reached by the one and two row windbreak treatments during the period of seed formation.

TABLE 23. Number of days to reach a phenological growth stage from seeding by zero, one, and two row east-west oriented windbreak treatments.

	Growth Stages[1]								
Treatment	VE	VC	V1	V5	R1	R3	R5	R6	R7
	days								
Zero Row	11[2]	15	27	50	54	68	81	104	*
One Row	11	15	27	50	54	68	81	103	*
Two Row	11	15	27	50	54	68	81	104	*

[1] Growth stages defined in Appendices 4 and 5.

[2] Soybeans seeded on May 21, 1982.

* Frost damaged before reaching this stage.

TABLE 24. The effect of east-west oriented zero, one, and two row windbreak treatments on plant height measured at three dates.

	Plant Height		
Treatment	July 19	August 9	August 23
	cm		
Zero Row	25.0 a*	59.8 a	69.4 a
One Row	28.3 a	67.6 a	80.3 b
Two Row	27.6 a	66.4 a	80.9 b
CV %	8.77	6.52	6.20

*Means within columns followed by the same letter are not significantly different at P = 0.05 (Duncan's Multiple Range Test).

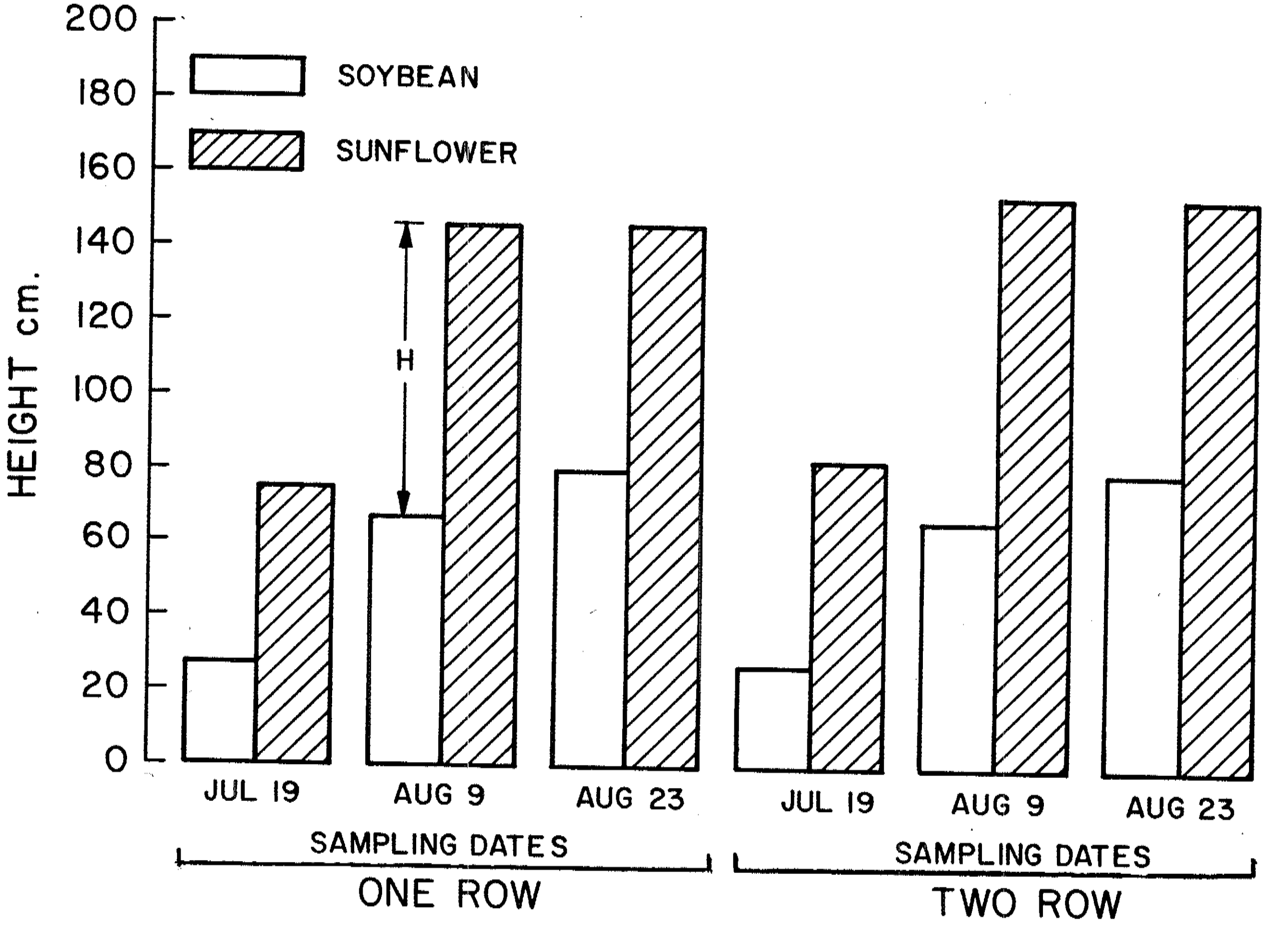

Figure 18. Height of soybeans, sunflowers, and effective windbreak height (H) measured at three dates for one and two row east-west oriented windbreak treatments in 1982.

Effective windbreak heights decreased to a constant value of 66 and 71 cm thereafter (Figure 18).

Leaf Area Index, Leaf Weight, and Leaf Area Ratio

Measurements of leaf area index, leaf weight, and leaf area ratio indicated that the treatments did not differ significantly (Table 25).

Top Dry Weight

Top dry weight determined at two different stages of growth did not indicate any significant difference between treatments (Table 26).

The vegetative growth parameters measured at different stages of growth indicated that even the east-west oriented windbreaks did not modify microclimate favourably for soybean growth and development. The probable reasons seemed to be that the unsheltered microclimate at Portage la Prairie did not induce stress on the soybean plants during the 1982 growing season. Secondly, the soybean cultivar, McCall, may be non-responsive to shelter.

Pod Number Per Plant, Harvest Index, Seed Yield, and Seed Weight

Measurements of the above yield parameters seemed to indicate that the east-west oriented windbreaks did not influence significantly these yield parameters (Table 27). The reasons used to explain the non-significance of vegetative growth parameters seemed to explain the non-significance of yield parameters among treatments.

Seed Quality

Seed quality as indicated by oil and protein content are shown in Table 28. Oil content did not vary significantly among treatments, whereas the zero and two row windbreak treatments differed significantly in protein content.

TABLE 25. The effect of east-west oriented zero, one, and two row windbreak treatments on leaf area index, leaf weight, and leaf area ratio.

Treatment	Leaf area index	Leaf weight (g/½ m row)	Leaf area ratio
Zero Row	2.76	36.2	73.2
One Row	3.02	39.7	73.9
Two Row	3.15	41.1	74.8
CV %	11.16	10.39	3.85

TABLE 26. The effect of east-west oriented zero, one, and two row windbreak treatments on top dry weight determined at two dates.

Treatment	Top Dry Weight August 18	 September 2
	g/m row	
Zero Row	207.2	445.0
One Row	223.9	453.8
Two Row	231.8	434.7
CV %	9.66	3.19

TABLE 27. The effect of east-west oriented zero, one, and two row windbreak treatments on pod number per plant, harvest index, seed yield, and seed weight.

Treatment	Pod number per plant	Harvest index	Seed yield	Seed weight
		%	kg/ha	g/1000 seed
Zero Row	34.9	42.9	1993	134.5
One Row	34.8	42.9	1943	138.5
Two Row	32.0	40.4	1950	142.6
CV %	8.15	5.99	5.48	5.01

TABLE 28. The effect of east-west oriented zero, one, and two row windbreak treatments on oil and protein content of seed.

Treatment	Oil		Protein	
	%		%	
Zero Row	20.4	a*	40.3	ab
One Row	19.3	a	39.7	a
Two Row	19.1	a	40.5	b
CV %	4.75		0.76	

*Means within columns followed by the same letter are not significantly different at $P = 0.05$ (Duncan's Multiple Range Test).

CONCLUSIONS

In contrast to findings reported in the literature, the annual crop parallel windbreaks used in this study did not influence favourably the vegetative growth and yield parameters measured in soybeans in Manitoba. It is also evident that the direction of annual crop windbreaks did not affect the growth, development and yield of soybeans in 1982.

Vegetative growth parameters such as plant height, leaf area and top dry weight were not significantly affected by windbreaks either in 1981 or 1982. The results also indicated that the permeability of the one and two row windbreak treatments did not affect significantly the vegetative parameters measured.

But, in 1981, summer fallow soil conditions promoted vigorous vegetative growth of sunflowers and produced windbreaks of low permeability for the two row windbreak treatment. Windbreaks of low permeability protected a small area leeward and caused stress conditions on soybeans due to increased turbulence. Higher canopy air temperatures also seemed to indicate stress conditions in soybeans grown under windbreak treatments. The trends in plant height, leaf area and top dry weight also indicated the unfavourable effects of windbreaks of low permeability. Low permeability of the two row windbreak treatment in 1981 seemed responsible for the significant decrease in the number of pods per plant and seed yield, and for the significant increase in seed weight and oil content of seeds. Stress conditions in the one row windbreak treatment seemed responsible for the significant reduction in number of pods per plant.

Higher temperatures in the sheltered zone of the two row windbreak treatment in 1981, seemed to be responsible for the significantly larger seeds and higher oil content of seeds.

In 1982, the barley stubble did not promote development of windbreaks of low permeability and hence did not result in adverse effects to soybeans grown even under two rows of sunflower windbreaks. Both vegetative and yield parameters did not differ significantly among the zero, one, and two row windbreak treatments.

Soybean water use determined between specified periods indicated that the total water use did not differ significantly between treatments in either 1981 or 1982.

Canopy air temperature patterns seemed to indicate that both the one and two row windbreak treatments in 1981 and the zero and two row windbreak treatments in 1982 were under moisture stress.

Air temperature patterns indicated that both higher and lower than normal temperatures prevailed in the sheltered zone and varied with locations where the temperatures were monitored.

The non-responsiveness of soybeans to parallel sunflower windbreaks seemed to be due to the fact that the unsheltered microclimate at Portage la Prairie in 1981 and 1982 did not promote physiological and/or physical stresses to soybeans. Further, because the wind direction was indeterminate, parallel windbreaks were only partly effective in ameliorating stress conditions. Hence, the windbreaks were not effective in improving the rate of phenological development, growth, and yield of soybeans at Portage la Prairie.

The other factor seemed to be the non-responsiveness of the soybean cultivar, McCall, to the sheltered microclimate.

The inability of annual windbreaks to provide shelter during the early vegetative growth phases of soybeans was also another possible factor for the non-responsiveness of soybeans to windbreaks.

RECOMMENDATIONS FOR FURTHER STUDIES

To understand the effect of windbreak modified microclimate on soybean growth under Manitoba climatic conditions, it is recommended that a preliminary study should be conducted to correlate soybean growth to microclimate modified by four sided and parallel temporary windbreaks established immediately before or after seeding.

Field studies are recommended with perennial shelterbelts or artificial windbreaks alone or with interspaced annual windbreaks so that response of soybeans to windbreak modified microclimate from emergence can be determined under natural conditions.

To understand the effect of turbulence, studies are recommended with zero, one, two, and four rows of windbreaks.

Different cultivars of the recommended maturity group of soybeans should be used to differentiate the responses of different cultivars to microclimates modified by annual and/or perennial windbreaks.

Field scale investigations should be carried out at different locations within Manitoba for many years to establish general response of soybeans to shelter under Manitoba climatic conditions.

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APPENDICES

APPENDIX 1. Supplementary nutrients.

Year	Nitrogen	Phosphate	Potassium
	kg/ha		
1981	8	41	0
1982	8	41	0

APPENDIX 2. Weed and insect control practices.

		Treatment				
Year	Date	Common name	Chemical name	Rate kg/ha	Application method	Comments
1981	May 26	Amiben	Chloramben (240 g/L)	2.22	Pre-emergence	
	June 22	Poast + 0.6% Assist Oil Concentrate	Sethoxydim (184 g/L)	0.26	Post-emergence	
	June 26	Basagran + 0.25% Citowett Plus	Bentazon (480 g/L)	0.96	Post-emergence	
	June 10	Lorsban	Chlorpyrifos 4 (479 g/L)	0.48		Against cutworm
1982	May 12	Amiben + Treflan EC	Chloramben (240 g/L) + Trifluralin (545 g/L)	2.22 + 0.95	Preplant incorporated	
	May 26	Roundup	Glyphosate (356 g/L)	1.07	Pre-emergence Post-emergence (weed)	Against thistle
	June 17	Poast + 0.6% Assist Oil Concentrate	Sethoxydim (184 g/L)	0.26	Post-emergence	
	June 22	Basagran + 0.6% Assist Oil Concentrate	Bentazon (480 g/L)	1.08	Post-emergence	

APPENDIX 3. Description of vegetative stages of soybeans.

Stage no.	Title	Description
VE	Emergence	Cotyledons above the soil surface.
VC	Cotyledon	Unifoliate leaves unrolled sufficiently so the edges are not touching.
V1	First node	Fully developed leaves at unifoliate nodes*.
V2	Second node	Fully developed trifoliate leaf at node above the unifoliate nodes.
V3	Third node	Three nodes on the main stem with fully developed leaves beginning with the unifoliate leaves.
V(n)	nth node	n number of nodes on the main stem with fully developed leaves.

*A node is considered to be fully developed when the leaf above it is sufficiently unrolled so the leaf edges are not touching.

APPENDIX 4. Description of reproduction stages of soybeans.

Stage no.	Title	Description
R1	Beginning bloom	One open flower at any node on the main stem.
R2	Full bloom	Open flower at one of the two uppermost nodes on the main stem with a fully developed flower.
R3	Beginning pod	Pod 5 mm long at one of the four uppermost nodes on the main stem with a fully developed flower.
R4	Full pod	Pod 2 cm long at one of the four uppermost nodes on the main stem with a fully developed leaf.
R5	Beginning seed	Seed 3 mm long in a pod at one of the four uppermost nodes on the main stem with a fully developed leaf.
R6	Full seed	Pod containing a green seed that fills the pod cavity at one of the four uppermost nodes on the main stem with a fully developed leaf.
R7	Beginning maturity (physiological maturity)	One normal pod on the main stem that reached its mature pod color.
R8	Full maturity	95% of the pods that have reached their mature pod color.

APPENDIX 5. Amount of water in the 0-120 cm soil profile at different sampling dates for zero, one, and two row windbreak treatments in 1981.

	Sampling Dates					
Treatment	Jul 13	Jul 20	Jul 27	Aug 4	Aug 14	Aug 27
	cm					
Zero	41.9	42.3	41.0	43.3	42.9	42.0
One	41.1	41.9	40.9	43.3	41.6	41.0
Two	41.5	42.4	41.4	43.4	42.0	41.0

APPENDIX 6. Amount of water in the 0-120 cm soil profile at different sampling dates for zero, one, and two row windbreak treatments in 1982.

	Sampling Dates				
Treatment	Jun 16	Jul 8	Aug 4	Aug 20	Aug 30
	cm				
Zero	51.5	50.7	52.1	49.5	48.3
One	49.7	48.6	48.5	47.0	46.0
Two	50.6	49.1	52.2	49.2	47.5