THE EFFECT OF TREE WINDBREAKS ON THE MICROCLIMATE AND CROP YIELDS IN THE WESTERN CAPE REGION OF SOUTH AFRICA

by

Andrew Gordon Hamlet

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Supervisor: Dr. J. M. Theron
Co-supervisor: Prof. G. van Wyk

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DECLARATION

I the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature Date

SUMMARY

The windbreak species near Wolseley (WoS1 and WoS3) was *Casuarina cunninghamiana*. The windbreak species near Saron (SaS1) and Villiersdorp (ViS1) was *Eucalyptus cladocalyx* and *Pinus radiata* respectively. A shelter effect was indicated at ViS1 (from northerly winds in winter/early spring 1999), and WoS3 (from southerly winds in late spring 1999).

Wind speeds were consistently reduced in the leeward sheltered zone of ViS1 and WoS3. To improve the correlation of the shelter effect, mild contaminating winds (comprising approximately 28% of the total data recorded at each site) were excluded for the prediction equations of the shelter effect at each site.

Compared to the more exposed wind speeds at 1.0 H to the windward side, wind speeds at ViS1 were reduced by 32% at 3.0 H. Compared to 11.0 H, wind speeds at ViS1 were reduced by 49 and 46% at 3.0 and 1.0 H respectively. With r^2 values above 93%, accurate linear prediction equations were produced. The early barley damage assessments indicated that damage was absent or negligible at 11.1 H to the lee, and significantly highest ($X < 0.05$) at 13.7 H to the lee and beyond. The crop shelter effect significantly increased ($p < 0.05$) barley head number, transformed proportion of total barley head^{mass} from above-ground^{mass}, potato tuber ^{mass}, potato above-ground^{mass} total potato tuber number, small tuber number, and disproportionate tissue damage to the windward section of each plant.

For WoS3, the shelter effect became pronounced with severe south-easterly winds. The average hourly wind speeds at 3.0 H dropped from 0.9 m / s (in the previous and less windy sampling period) to 0.8 m / s, despite the sharp increase in exposed wind speeds. Compared to 13.0 H, wind speeds were reduced by 73 and 32% at 3.0 and 7.0 H respectively. With r^2 values above 94%, accurate linear prediction equations were produced. The crop shelter effect significantly increased ($p < 0.05$) sub-sample^{mass} of 100 grains.

At WoS3, strong and sustained wind speeds caused leeward soil temperature increases of up to 4°C at 3.0 H, compared to 11.0 H. Brief strong winds (characteristic of winds at ViS1) had little effect on the soil temperature differences. At ViS1, a deviation of soil moisture content between 3.0 and 11.0 H, following periods of recharge, indicated a potential soil-moisture conservation effect in the sheltered zone. This did not occur at WoS3, due partly to a very low soil moisture content that had little scope for variation.

From the crop variations and the microclimate variations at both ViS1 and WoS3, the maximum shelter effect extended to approximately 4.0 H, followed by an intermediate zone of diminishing shelter that extended to approximately 9.0 H.

For ViS1, WoS3 and SaS1, a shading effect significantly reduced yields ($p < 0.05$) at 1.0 H from the respective northern windbreak, compared to yields at 2.0 H. At ViS1 and WoS3, soil probes did not indicate a depletion of soil moisture resulting from the respective windbreaks. Soil moisture competition was indicated on the northern side of the WoS1 windbreak with drier conditions; where soil moisture levels at 1.0 and 3.0 H diverged from a negligible level to a 22% lower level ($p > 0.05$) at 1.0 H, compared to 3.0 H.

OPSOMMING

Die boomsoorte wat as windbreke gedien het was *Casuarina cunninghamiana* naby Wolseley (WoS1 en WoS3), en *Eucalyptus cladocalyx* en *Pinus radiata* by Saron (SaS1) en Villiersdorp (ViS1) respektiewelik. Beskutting is aangetoon by ViS1 (teen noordelike winde in winter/vroeë lente 1999) en WoS3 (teen suidelike winde in laat lente 1999).

Windspoed is konsekwent aan die lykant sones van ViS1 en WoS3 verminder. Ten dien einde die korrelasie van die beskuttings effek te verbeter, is matige kontaminerende winde (ongeveer 28% van die totale waargenome data by elke plek) buite berekening gelaat vir die voorspellingsvergelykings van die beskuttingseffek.

In vergelyking met die meer blootgestelde windspoede by 1.0 H aan die windkant, is windspoede by ViS1 met 32% verminder by 3.0 H. In vergelyking met 11.0 H is windspoede by ViS1 met 49 en 46% by 3.0 en 1.0 H respektiewelik verminder. Met r^2 waardes hoër as 93%, is akkurate lineêre voorspellingsvergelykings verkry. Die vroeë gars skade opnames het aangetoon dat geen of minimale skade by 11.1 H aan die lykant aangerig is, en beduidend die hoogste ($x< 0.05$) by 13.7 H en verder aan die lykant was. Die gewas beskuttins effek het beduidende toenames ($p< 0.05$) in gars-are, getransformeerde verhouding van totale gars-are massa van bo-grondse massa, aartappelknol massa, aartappel bo-grondse massa, totale aantal aartappelknolle, en oneweredige weefsel beskadiging aan die windkant van elke plant tot gevolg gehad.

Vir WoS3 het die beskuttingseffek beduidend geword met baie sterk suidoostelike winde. Die gemiddelde uurlike windsnelhede by 3.0 H het van $0.9/^s$ (in die vorige en minder winderige toetstydperk) tot 0.8 $m/^s$ verminder, ten spyte van die skerp toename in blootgestelde windsnelhede. In vergelyking met 13.0 H is windsnelhede met 73 en 32% by 3.0 en 7.0 H respektiewelik verminder. Met r^2 waardes hoër as 94% is akkurate lineêre voorspellingsvergelykings verkry. Die gewas beskuttingseffek het sub-monster massa van 100 graankorrels beduidend ($p< 0.05$) verbeter.

By WoS3 het sterk en volgehoue windsnelhede grondtemperature aan die lykant met tot 4°C by 3.0 H verhoog in vergelyking met 11.0 H. Kortstondige sterk winde (tipiese winde by ViS1) het weinig uitwerking op grondtemperatuursverskille gehad. By ViS1 het 'n afwyking van grondwaterinhoud tussen 3.0 en 11.0 H na tydperke van aanvulling, 'n potensiële grondwaterbewaringseffek in die beskutte gebied getoon. Soortgelyke tendense het nie by WoS3 voorgekom nie, gedeeltelik as gevolg van 'n baie lae grondwater inhoud wat nie veel kon varieer nie.

Van die variasies wat in gewasse en mikroklimaat voorgekom het, by beide ViS1 en WoS3, kan afgelei word dat maksimum beskutting tot by ongeveer 4.0 H verleen is, gevolg deur 'n intermediêre sone van verminderende beskutting tot ongeveer 9.0 H.

Vir ViS1, WoS3 en SaS1 het 'n skadu-effek gewasopbrengs beduidend ($p< 0.05$) by 1.0 H verminder in vergelyking met opbrengste by 2.0 H. By ViS1 en WoS3 het grondwater strooiingspeilers nie 'n uitputting van grondwater as gevolg van die windbreke getoon nie. Kompetisie vir grondwater is getoon aan die noordelike kant van die WoS1 windbreek met droër toestande.

Grondwatervlakke by 3.0 H het minimaal maar by 1.0 H met 22% beduidend ($p> 0.05$) teenoor 3.0 H gedaal.

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CHAPTER 1

AN INTRODUCTION TO THE POTENTIAL BENEFITS OF WINDBREAKS IN THE WESTERN CAPE REGION OF SOUTH AFRICA

This chapter aims to provide a concise introduction for three following chapters, concerning the potential benefits of windbreaks on farms in the Western Cape Region of South Africa.

1 PROBLEM STATEMENT AND PROJECT OBJECTIVES

Severe winds in the Western Cape are an unavoidable problem for farmers throughout the region. The severe hot and dry south-easterly winds in spring and summer are suspected to cause significant crop yield reductions. Severe north-westerly winds in winter are also prevalent in some areas of the Western Cape. Despite the potentially significant benefits of windbreaks on farms in the Western Cape Region, there are still many vast areas that remain unprotected by windbreak, especially in the pastoral areas. Conversely, orchardists in the Western Cape Region have embraced the windbreak technology, planting extensive networks throughout their farms.

Effective windbreaks are an economically sound investment for all farmers, so this absence of windbreak systems on farms in the Western Cape Region does not make much sense. To compound the lack of awareness concerning windbreaks in the Western Cape Region of South Africa, there has been very little local research. This lack of research must be a significant obstacle to the development of windbreak systems on a large scale.

Information based on critical field observations and experimental studies on the potential benefits of windbreaks in South Africa is limited, despite large numbers of windbreaks existing in mainly the orchard growing regions. Therefore, this project aims to provide some practical and local evidence of the benefits of tree windbreaks on selected farms in the Western Cape Region. A culture of windbreak research and technology must be encouraged to foster a greater acceptance of windbreaks on farms within this targeted region.

- **Chapter 1** aims to provide a concise introduction for three following chapters
- **Chapter 2** aims to investigate the variation of wind speed, temperature, and soil moisture content in relation to the distance from existing windbreaks in the Western Cape Region.
- **Chapter 3** aims to investigate crop yield variation in relation to the distance from existing windbreaks in the Western Cape region.
- **Chapter 4** aims to conclude the windbreak effects discussed in the previous chapters, followed by recommendations of windbreak management to optimise the potential benefits of windbreaks on farms in the Western Cape Region.

Ultimately, the project aims to encourage the development of windbreak networks throughout the Western Cape Region (and other parts of South Africa) for the benefit of all communities, especially those in the rural sectors.

2 BACKGROUND

2.1 Benefits of windbreaks

The principle effect of windbreak shelter is to alter the pattern of average wind velocity and turbulence to improve microclimate conditions for physiological processes as well as to reduce physical damage to vegetative plant parts (Cleugh, 1998; Haigh, 1994; Sun and Dickinson, 1994; McNaughton, 1988). Windbreaks reduce wind speeds by exerting a drag force on the wind field. This produces a triangular 'quiet' zone of reduced turbulence and eddy size, below a line beginning at the top of the windbreak and extending leeward to a distance at ground level. Passing near the top of the barrier and growing downwind of the quiet zone is a turbulent 'wake' zone (Cleugh and Hughes, 2000; Zhang *et al.*, 1995; Heisler and Dewalle, 1988; McNaughton, 1988).

A reduction in wind speed is likely to cause an increase in humidity because there is less turbulent transfer of water vapour away from the crop. This increase in the vapour pressure of the air may correspond with a decrease in the vapour pressure deficit between air and leaf. As a consequence, a reduction in the convection rate (transpiration rate) may occur, resulting in a saving of stored soil moisture for later use. This ultimately improves soil moisture conservation and crop water-use efficiency, resulting in increased growth and improved yield and quality of the sheltered crops (Nuberg, 1998; Davis and Norman, 1988; Dickey, 1988). Wind damage is generally admitted to be an important limiting factor facing South African orchardists (Myburgh and Viljoen, 1979; Pienaar, 1987).

International research over the last 50 years suggests that the reduction of wind speed by tree windbreaks can increase crop productivity by 5 to 25% (Brandle *et al.*, 1992). Despite average yield increases over the entire field, there may be a negative interaction caused by the windbreak resulting from competition with pastures or crops for mainly soil moisture (Nuberg, 1998; Yunasa *et al.*, 1995; Puri and Bangarwa, 1992; Kort, 1988). Some farmers believe that trees significantly reduce total crop yields, and therefore avoid planting trees (Khan and Ehrenreich, 1994). Excessive water extraction by *Eucalyptus* has become a highly controversial issue in India, Burma, Tanzania and South Africa where these trees were used extensively for plantation purposes (Eastham and Rose, 1988). The extent of the competition effect is further discussed in Section 1.3.2 $_{\text{Ch. 1}}$.

However, the yield benefits on a net return basis are expected to more than compensate for the competitive interaction between trees and crops (Brandle *et al.*, 1992; Bird, 1991). In maize and groundnut alley systems in India, the increased relative humidity in the sheltered zone decreased transpiration rates of crops. This resulted in yields of 0.89 t/ha in the sheltered crop and 0.68 t/ha in the exposed crop, which was a 31% yield increase due to shelter (Srinivasalu and Jaganatham, 1992). In the semi-arid tropical highlands of Kenya, increases in maize yield of 50 to 80% suggested a *Grevillia robusta* shelter effect due to the enhanced water-use efficiency (Huxley *et al.*, 1994). Careful selection and management of tree and crop species is essential to reduce competition for soil moisture at the tree / crop interface (Nuberg, 1998 ; Sanchez, 1995 ; Kort, 1988).

On a local level, a model used by Van Asten *et al.* (1997) based on a market garden in the Western Cape of South Africa, indicated that a 50% reduction in wind speed resulted in a 20% reduction in evapotranspiration; with the benefit increasing with increased temperatures and wind speeds. However, such a fortunate sequence of events does not always occur. For example, Brenner *et al.* (1995a) in the Sahel region of Africa, measured an increase in transpiration of sheltered millet due to higher leaf temperature and stomatal conductance than in unsheltered crops.

Another important benefit provided by windbreaks is the protection of the soil from wind erosion. Soil protection offered by windbreaks is most valuable in regions of friable and poorly structured soil, under farming systems where the bare soil is exposed and especially during the dry period of the year (Nuberg, 1998). As soil erodes, its productivity decreases due to the loss of fine soil particles containing organic matter and nutrients (Kort, 1988; Williams *et al.*, 1981). Wind erosion control on sand dunes and other problem areas requires further intensive measures. In several places on the South African coast, sand dune erosion has destroyed vast areas of farmland and has even threatened entire communities (Van Rensburg, 1973). Wind erosion damage in South Africa continues to increase in magnitude at astronomical proportions. It has become such a common phenomenon in some parts of the country that the population has accepted the consequent damage and unpleasant living conditions as normal (Esterhuyse, 1994).

Either soil losses are made up by the addition of fertilizer (which increases crop production costs), or yields are reduced which lower economic returns (Brandle *et al.*, 1992). When winds erode soil during field preparation and planting, herbicides and nutrients applied to the surface are lost. Soil blown from a field contained an estimated 10 to 20 times the organic matter and phosphates as the heavier particles that remained (Hagen and Lyles, 1985). By controlling wind erosion, windbreaks limit long-term losses in soil productivity and reduce the need for added inputs. Therefore, the reduction of these losses by wind erosion can be an additional benefit flowing from the windbreak investment (Esterhuyse, 1994; Brandle *et al.*, 1992).

When aligned along contours of sloping lands to provide a continuous barrier, windbreaks can also decrease surface runoff and erosion. This may further reduce the competitive interactions (Kiepe and Rao, 1994). Erosion between windbreaks was generally much less in sheltered locations (compared to unsheltered locations), as indicated by depths of carbonates in experiments conducted by Kowalchuk and De Jong (1995). Thus, potential productivity of the soil in sheltered fields would be higher than unsheltered fields by this aspect alone. Subsequently the actual yield benefits of windbreaks may be greater than estimated in studies that are concerned with crop evapotranspiration only (Kowalchuk and De Jong, 1995).

Windbreak trees can also provide one of the most effective and cheapest methods of preventing heat stress to domestic stock. For example, dairy cattle experience stress when the temperature rises above 25°C resulting in increases of water uptake by 20 to 30%. The effect of this added stress might cause a reduction in milk yield of 10 to 40% and in butterfat content of 20 to 40%. Fertility of cows may drop from 65% to less than 40%. Hot sunlight may break down sheep wool fibres, reducing the fleece yield. Shelter from cold adverse conditions will conserve energy, thereby requiring less food intake and reducing the possibility of physical injury or death (Haigh, 1994). By increasing pasture yields and changing the microclimate to reduce maintenance energy requirements of livestock, windbreaks can subsequently increase livestock production and survival (Esterhuyse, 1994; Khan and Ehrenreich, 1994).

Windbreaks may provide a wide range of useful products, such as poles, fuel-wood, fruit, fodder, fibre, and mulch (Puri *et al.*, 1992). A good example of these benefits occurs in farmlands in Pakistan, which provide a third of the timber and 90% of the fuel needs of the nation (Amjad and Khan, 1988).

Honey production can be a valuable by-product of windbreaks. If this is a major consideration, then tree species that are high producers of nectar and / or pollen should be selected. Planting a variety of species will allow flowering to occur over as many months of the year as possible. An increase in the bee populations brought about by planting suitable flowering trees will benefit any agricultural crops requiring pollination, thereby further encouraging greater crop yields. Some suitable honey production trees in frost-free areas of South Africa include *Eucalyptus grandis, Eucalyptus maculata, Eucalyptus microcorys*, and *Eucalyptus paniculata* (Haigh, 1994). *Eucalyptus caladocalyx* should also be included as a suitable honey production tree in the Western Cape Region. The reduction of wind speed by windbreaks also encourages bee flight into crops (Norton, 1988).

Windbreaks increase populations of natural pest enemies, thus reducing the need to artificially control pests using toxic chemical substances that may be a health hazard to humans and livestock (Esterhuyse, 1994). Windbreaks provide valuable wildlife habitat, providing the only significant woody vegetation in some areas. While increased habitat may become a refuge for some wildlife that damages crops, the overall benefits are positive and the ecological and economic advantages were estimated to be high. Thus, society may also be a recipient of numerous benefits from a cultural pattern of field windbreak establishment (Bird, 1991; Cable and Cook, 1990; Johnson and Beck, 1988). Windbreaks on farms offer diversification of the farm enterprise that offer a better opportunity for survival in terms of crises, such as periods of drought or over-production (Esterhuyse, 1994).

2.2 Extent of the competition effect

Kang *et al.* (1985) found that *Leucaena* trees in sub-tropical Nigeria concentrated soil-water uptake at deeper levels in the soil profile compared to wheat, which reduced competition with the annual crops. *Grevillia robusta* hedgerows in sub-tropical Kenya tended to concentrate roots beyond 2 m depth, which possibly improved niche differentiation for below-ground resource capture (Huxley *et al.*, 1994). To examine the below-ground complementarity in water between grevillia and cowpea in Kenya, Howard *et al.* (1997) used heat balance sap gauges attached to tree stems to measure sap flux; before and after excavating the crop's rooting zone in the upper 60 cm of soil around the stem base. After excavation, the trees maintained sap fluxes of up to 85% of the unexcavated values, suggesting a high degree of below-ground complementarity for this particular species.

In the Sahal, Smith *et al.* (1998) used a stable isotope technique to compare the utilisation of ground water by windbreaks and crops at two sites in Niger with different water table levels. At the site where the water table was accessible, the windbreaks used spatially distinct sources of water. At the site with an inaccessible water table, competition for water occurred at the zone where trees, like adjacent crops, rely on water from the top of the soil profile. During periods of drought at the latter site, such competition for water was suspected to be severe. The extent of the competition zone may therefore depend on the ability of a tree species to both access the watertable and to conserve water requirements. Potential competition was most severe with *Acacia nilotica and Acacia* *holosericea*, both of which extracted large quantities of water through lateral roots, and at the location where trees could not access ground water. *Azadirachta indica* used the lowest amount of water, probably resulting from lower stomatal conductance compared to the former species.

Schroth and Zech (1995) also reported that ideal windbreak trees should have low root competitiveness and a root distribution complementary to that of the crop. This may be difficult for areas where soils are typically shallow and soil moisture is limiting, which is typical of most temperate cropping zones. Nevertheless, knowledge of the root system morphology of specific windbreak species would help determine complementarity and also resilience to root pruning.

Models have been developed recently that provide a relationship between proximal root diameter close to the tree stem and total root surface area (Van Noordwijk and Purnomosidhi, 1995; Van Noordwijk *et al.*, 1994), thus providing an index for tree root competitiveness. Models such as these have only been developed for humid tropical conditions, therefore basic work needs to be done before such methods can be used for temperate conditions. Such information would be an invaluable tool to characterise the root systems of candidate species for temperate windbreak systems. Emphasis in previous selection and breeding programmes for multi-purpose trees has usually been directed towards above-ground characteristics, but it is clearly essential to include complementarity of root behaviour in the selection criteria (Howard *et al.*, 1997; Ong *et al.*, 1996).

Some eucalypts have been reported to be too competitive for windbreaks regardless of any shelter effect. Malik and Sharma (1990) reported yield reductions of 47% in mustard and 34% in wheat within 11.0 m strips adjoining windbreaks of *E. tereticornis*. Windbreak height was not given in the report. Puri and Bangarwa (1992) in the semi-arid regions of India reported that *Azadirachta indica* and *Prosopis cineraria* windbreaks did not have any significant effect on wheat yield, while *Dalbergia sissoo* and *Acacia nilotica* showed a reduction in wheat yield. *A. nilocota* had the most significant effect, reducing wheat yield by up to 60% as far as 7.0 m, and *D. sissoo* reduced yields up to a distance of 3.0 m. *A. nilotica* also intercepted light that resulted in decreased photosynthetic activities of wheat and thus further decreased wheat yields. In the same region, Puri *et al.* (1992) reported yield reductions of 38% for wheat, 41% for chickpeas and 49% for *Trifolium alexandrinum* grown next to windbreaks of *A. nilotica*. The competition zone of this species also extended to 11 m from the windbreak. Thus, species such as *A. nilotica* were not recommended for planting with crops.

There is potential for considerable competition for nitrates between tree and crop roots in the topsoil (Gillespie, 1989). Balasubramanian and Sekeyange (1991) reported that all five N-fixing tree species in an experiment caused crop yield reductions due to competition for moisture and / or light rather than nutrients. Crop yields were reduced even when manure was applied to the crops to minimise the nutrient deficits, indicating that nutrient competition played an insignificant role in yield reduction.

Direct competition for water and nutrients is not the only negative interaction that windbreak trees can have with crops. The allelopathic effects from trees such as *Eucalyptus tereticornis* and *Eucalyptus camaldulensis* have been implicated as the cause for low yields in otherwise sheltered zones (Nuberg, 1998). From personal observations, *Casuarina cunninghamiana* shows a lower level of allelopathy compared to most Eucalypts.

2.3 Dynamics of windbreaks

The extent of the windbreak effect depends on windbreak height, porosity, orientation, profile, and location in the landscape. Windbreak height is so important that the convention used to describe the distance away from a windbreak is in terms of a normalised unit, i.e. 1.0 H = 1 tree height. Therefore, the protected zone associated with a windbreak is directly proportional to the height of the windbreak (Nuberg, 1998). Where the main priority is to protect valuable crops and pasture, windbreaks should be as tall and as far apart as possible to obtain the most protection for the least amount of farmland devoted to trees (Finch, 1988; Rocheleau *et al.*, 1988).

Porosity is important because it determines the extent to which a windbreak reduces the kinetic energy of the wind by filtering the airflow. An impermeable windbreak will obstruct and deflect airflow, creating a small but very sheltered zone close to the windbreak (up to 10 H but usually considerably less) before turbulent wind eddies contact the ground. Such dense windbreaks may do more harm than good by creating strong air currents that will scour the soil on the upwind side and damage crops on the downwind side. In contrast, a permeable windbreak of 40 to 50% porosity will diffuse the airflow, thereby creating a low speed cushion of air (regarded as the sheltered zone) over an optimum distance before turbulent flow contacts the ground (Nuberg, 1998; Zhang *et al.*, 1995; Haigh, 1994; Sun and Dickinson, 1994). A local investigation by Viljoen (1979) used a variety of artificial barriers of different porosities to reach similar conclusions.

From a series of wind tunnel measurements, Cleugh and Hughes (2000) suggested that the spatial pattern of the sheltered zone does not vary with windbreak porosity, assuming a uniform vertical porosity profile. This implies that windbreak porosity determines the amount of windbreak shelter, while windbreak height determines the leeward extent of windbreak shelter.

Windbreak profile is not of great importance. A sloping profile, obtained by planting shorter species on the outside rows, is not necessary. A uniformly permeable and tall vertical face is the desirable structure. Single-row tree windbreaks can provide wind reductions over as great a distance as multiple-row windbreaks (Heisler and Dewalle, 1988; Schroeder, 1988; Sturrock, 1969, 1972). The influence of width seems to be primarily important to the degree that it influences porosity (Woodruff *et al.*, 1963). Trees with narrow, vertical growth minimise the land removed from crop production and are hence ideal for windbreaks (Bird *et al.*, 1992). The only disadvantage of single row windbreaks is the potential lack of continuity from the loss of trees, which will have a serious effect on the efficiency of the windbreak (Haigh, 1994; Finch, 1988). For this reason, Haigh (1994) advised that windbreaks should be wider than one row. Depending on tree crown development and eventual height, row spacing may be from 3 to 5 m with trees in one row planted opposite the gaps in the next row to form a staggered pattern.

The ratio between length and height of a windbreak is also important. This ratio should be at least 15:1 to reduce the proportion of air sucked around the sides of the windbreak. From wind tunnel experiments, Cleugh and Hughes (2000) suggested that windbreaks that were 20 H in length were sufficiently long that the edge effects did not significantly erode the size of the sheltered zone.

Windbreaks are most effective when orientated normal (perpendicular) to the prevailing wind direction. Deviation of wind direction may change the effective porosity and reduce wind speed reduction in shelter. Therefore, the windbreak should be orientated to face the primary prevailing wind direction to ensure maximum shelter benefits (Puri *et al.*, 1992; Heisler and DeWalle, 1988; Hagen, 1976). However, the downwind pattern of shelter was not significantly reduced by deviations up to 45° to the normal wind direction (Cleugh and Hughes, 2000). The prevailing winds of the Western Cape Region are mainly south-easterly and north-westerly. In this region, windbreaks that are orientated east to west will be effective against both of these destructive winds (Myburgh and Viljoen, 1979).

Almost all research of windbreak flows has been based in flat locations. However, windbreaks are just as likely to be located in undulating topography that modifies airflow. Intelligent planning of windbreaks therefore requires an understanding of the effect of topography on the speed and direction of regional winds (Cleugh and Hughes, 2000). The effect of slope and aspect on radiation receipt, water-holding capacity of the soil, and elevation effects on air temperature may have a greater impact on crop microclimates in hilly terrain than the effects of shelter alone (Raupach and Finnigan, 1997).

Windbreaks will be most effective if placed in regions where the topography enhances the wind speed (such as valleys and ridges), and orientated normal to the prevailing wind direction (Cleugh and Hughes, 2000). From wind tunnel experiments conducted by Cleugh and Hughes (2000), the maximum shelter benefit occurred by placing a windbreak at the crest of a hill, where wind speed was accelerating and velocities were large. The effectiveness of a windbreak placed in a hill's wake zone might be significantly reduced if the hill's wake boundary intercepts with the windbreak's wake boundary. The same authors' also noted that a very rough landscape in an aerodynamic sense (due to trees or tall crops) resulted in a greater approach flow turbulence and subsequently a greater level of local shelter, compared to an identical windbreak placed in terrain that was much less rough (such as grazed pasture).

A slope of 10% will halve the sheltered distance relative to no slope. A spacing interval of 2.0 H is recommended for slopes above 30%. Depending on the prevailing wind direction, windbreaks should be planted on contours to protect the upper slope and the ridge (King and Sturrock, 1984).

2.4 Economics of windbreaks

Most farmers will require quantitative evidence of an economic return from establishing windbreaks (Nuberg, 1998). Before a large-scale programme begins, information on wind and other climatic factors should be gathered and analysed for the area (Rocheleau *et al.*, 1988). A long-term management plan should be compiled for each farm so that trees become an integral part of the farm ecosystem and enterprise. There is a need to develop a detailed economic analysis of the benefits of windbreak protection, as indicated by Brandle and Hintz (1988). In particular, it is necessary to develop the ability to determine if a windbreak under various economic circumstances remains a desirable investment. Economic profitability of windbreak investments is based on costs and benefits over time. These include the value of foregone production costs resulting from land taken out of production, and establishment costs (such as fencing, trees, fuel, herbicide, labour and management where charged). The unproductive period while the windbreak matures, and any alterations in the cost of crop production due to the windbreak, should also be included (Brandle *et al.*, 1992; Bird, 1991; Kort, 1988). Benefits include extra gross margins resulting from anticipated yield increases in crop and livestock production.

Model experimental conditions for windbreaks might be easier to control compared to *in situ* windbreak experiments. Therefore, it is possible to obtain more and better information on the aerodynamics of shelter from model tests because it is easier to make measurements on scalar models. Model experiments also allow the study of mechanisms responsible for creating shelter microclimate without the complicating effects of vegetation responses (McNaughton, 1988).

Models produced by Brandle *et al.* (1992) and Bird (1991) evaluated the net revenue generated over the windbreaks economic life. A net present value (NPV) approach was used, whereby the benefits of the investment in terms of future income flows were discounted to present value terms, from which the cost of the investment was then subtracted. Using a computer model of a southern Australian farm to simulate the economic effects of planting trees, Bird (1991) predicted that productivity of the land was progressively increased and stock losses decreased over time, as the trees grew and as more windbreaks were planted. Models with various combinations of wheat, cotton, and sugarcane with windbreaks of eucalypts, poplars, and shisham were developed by Fazli (1990) using the NPV approach for three regions in Pakistan. Yield depressions near the windbreaks were incorporated into the models. All systems were more profitable compared to unsheltered crops, even with a discount rate of 12%. The timber and fuel-wood value of windbreaks clearly outweighed the significant competitive effect of trees on crops in this environment.

Comparing different crops (wheat, corn, and soybean) at a variety of discount rates indicated that the yield increase needed to justify the investment only slightly depends on the crop (Brandle *et al.* 1992). Using a net present value approach, an investment in a field windbreak occupying 5% of the field was economically viable over a wide range of economic and production conditions. Long term yield improvements of as little as 6% more than compensated for establishment costs and the loss of output from land taken out of production. Discount rates of crop species significantly influenced the crop yield increase required to justify the windbreak investment. Nevertheless, discount rates as high as 17% in southern Australia still yielded positive net present values with annual crop increases of as low as 10%. Additional costs resulting from tree replanting and weed control would have minimal effects on the investment viability. Windbreaks would remain economically viable as long as there was yield increases of 10% or more for even the most costly establishment situations. Furthermore, the producer could spend enough money per tree to also cover the cost of a drip irrigation system, and still need only a 10% yield increase to have a positive net present value.

From models of a range of windbreak systems on a typical New Zealand sheep farm (Horvath *et al.,* 1997b), pasture production and lamb survival increased due to shelter, increased profits by 90% over a 43-year period. The timber sales alone would provide 70%, and the other 20% occurred from gains in pasture production and lamb survival

Comparisons were made by Bird (1991) concerning the costs and benefits of planting 3-row or 6-row windbreaks at 500 m or 250 m spacing (5 to 20% of the farm), with a 400 ha property with no windbreaks. The computer model calculated that if at least 5% of the farm can be devoted to a shelter network, then even at the highest discount rates the financial profitability of the farm would increase in the long term. When a windbreak network occupied 10% of the farm, the outcome depended on the discount rate used, and on the distribution of the trees. As 3-row windbreaks formed an effective windbreak, it was best to increase the network of windbreaks rather than have fewer but wider (6-row) windbreaks.

This same model also predicted that it was better to devote 10% of the farm to close spaced windbreaks rather than 5% in a wider spaced network, despite increased fencing costs and loss of extra grazing area. In all options, the farmer could hire labour to do all work associated with the project and the enterprise would remain viable. However, only at low discount rates of 17% and when the farmer does the work, can 20% of the farm be devoted to windbreaks without economic penalty. Other factors such as salinity control or timber production may justify such a step. At least 10% of the farm devoted to windbreak networks was undoubtedly profitable in the higher grazing areas of southern Australia, which is comparable to the climate of the Western Cape Region in South Africa. By using a combination of annual barriers within a backbone of tree windbreaks, a farmer could achieve immediate protection while investing in a long-term solution (Bird, 1991). Use of the zone next to the tree row for field access could further reduce the area negatively affected by the windbreak network (Brandle *et al.,* 1995).

The greater the protective and productive benefits, the better the chance of co-operation among the land users over large expanses of land (Rocheleau *et al.*, 1988). Incentive schemes could provide additional income during the establishment period and result in an immediate positive cash flow (Brandle *et al.*, 1992; Ritchie, 1988).

3 APPROACH TO RESEARCH

3.1 Site Criteria

An approach for concise windbreak information is to establish and monitor tree networks under specific experimental designs over a cycle, which might require 5 to 20 years depending on the species and other factors. Another approach involves research on existing trees, which is far more feasible if the period of the research is limited to a few years (Puri and Bangarwa, 1992). Therefore, site selection for this particular project focused on farms that had established windbreaks with the possibility for crop establishment and crop sampling on adjoining vacant land to the leeward side of the windbreak. All selected sites were within 1-hour driving range from Stellenbosch.

At each research site, windbreaks were measured for average effective tree height, which was regarded as the height from which consistent shelter was provided (Nuberg, 1998;

Finch, 1988; and Rocheleau *et al.*, 1988). Therefore, units of average tree height (H) were used to quantify the extent of shelter from the windbreak.

Farmers were interviewed to assess their co-operability and their opinions of research aims and methods on the selected sites. The windbreak had to be well orientated with a consistent height, profile, and porosity to intercept prevailing winds that occurred frequently and from a consistent direction. The soil homogeneity across the site was also important, with as little change in elevation as possible. To restrict the area of the site to a minimum, younger windbreaks of a small height (ranging from 5 to 10 m) were favoured for research. The smaller the trees the better, because this would limit the distance to be sampled on each side of the windbreak and would minimise possible nutrient re-distribution which occurs over time (Bird, 1998). The same author also stated that measurements of the shelter effect could occur when the trees were as small as 5 m high.

3.2 Site selection

During 1998, research was based on two farms, one farm near Wolseley (12 km south-west of Ceres) and the other near Saron (25 km south of Porterville). In 1999, research shifted to two other farms, one also near Wolseley and the other 10 km west of Villiersdorp. Two research sites, Wolseley Site 1 (WoS1) and Wolseley Site 2 (WoS2), were located on the same farm. There were three other sites, at Saron Site 1 (SaS1), Wolseley Site 3 (WoS3), and Villiersdorp Site 1 (ViS1). The windbreak species at the three Wolseley sites was *Casuarina cunninghamiana*. The windbreak species at SaS1 was *Eucalyptus cladocalyx*, and the windbreak species at ViS1 was *Pinus radiata*. The locations of the research sites in the Western Cape Region are shown in Plate 1.1 $^{\text{Ch. 1}}$, and views of each site are shown in Plates 1.2 to 1.6 $^{\text{Ch. 1.}}$

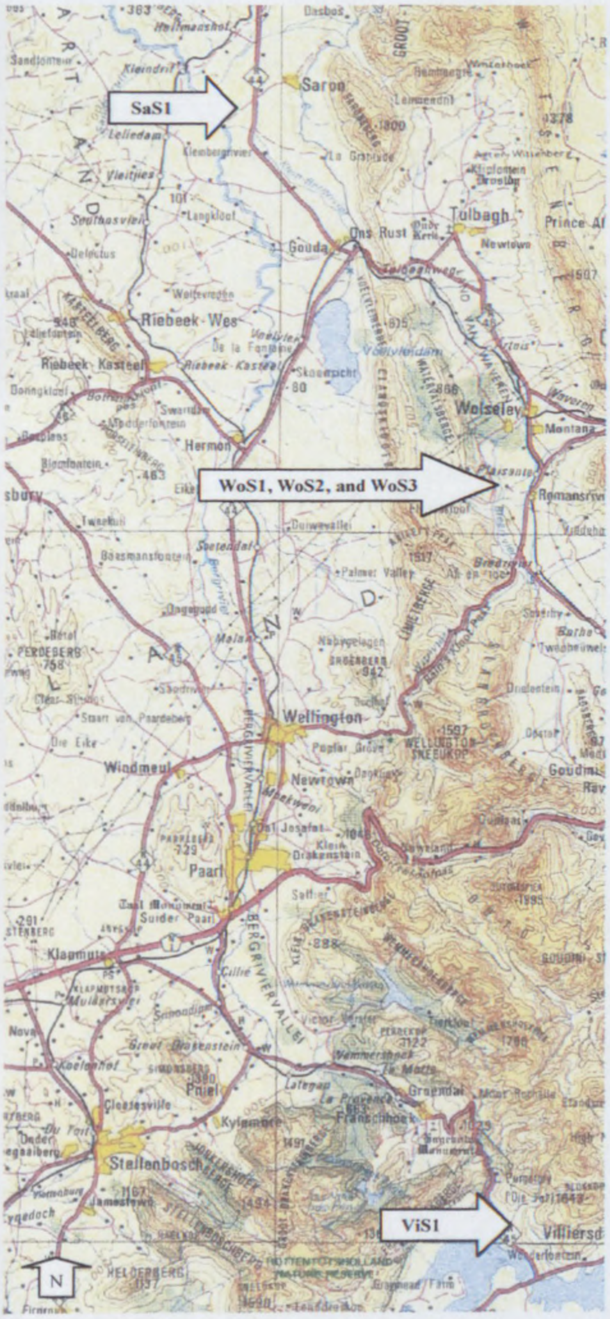

Plate 1.1 Locations of the five sites

Plate 1.2 View of the northern *P. radiata* windbreak at ViS1

Plate 1.3 View of the southern *C. cunninghamiana* windbreak at WoS3

Plate 1.4 View of the northern *E. cladocalyx* windbreak at SaS1

Plate 1.5 View of the southern *C. cunninghamiana* windbreak at WoS1

Plate 1.6 View of the southern *C. cunninghamiana* windbreak at WoS2, partially sheltering a pear orchard.

4 REFERENCES

Amjad M. and Khan N. (1988) The state of forestry in Pakistan. Forest Economics Branch, Pakistan Forest Institute Peshawar, Pakistan, 103 pp. In: Khan G. and Ehrenreich J. (1994) Effect of increasing distance from *Acacia nilotica* trees on wheat yield. Agrofor. Syst. 25: 23 - 29.

Balasubramanian V. and Sekeyange L. (1991) Effects of tree legumes in hedgerows on soil fertility changes and crop performance in the semi - arid highlands of Rwanda. Bio. Agric. Hort. 8: 17 - 32.

Bird PR. (1998) Tree windbreaks and shelter benefits to pasture in temperate grazing systems. Agrofor. Syst. 41: 35 - 54.

Bird PR., Bicknell D., Bulman PA., Burke SJA., Leys JF., Parker JN., Van Der Sommen FJ. and Voller P. (1992) The role of shelter in Australia for protecting soils, plants and livestock. Agrofor. Syst. 20: 59 - 86.

Bird PR. (1991) Tree and shelter effects on agricultural production in southern Australia. Agric. Sci. 4 (5): 37 - 39.

Brandle JR., Hodges L. and Stuthman J. (1995) Windbreaks and speciality crops for greater profits. In: Agroforestry and sustainable systems: symposium proceedings. USDA For. Serv. Gen. Tech. Rpt. RM - GTR - 261. In: Hodges L. and Brandle JR. (1996) Windbreaks: an important component in a plasticulture system. Hort. Technology 6: 177 - 181.

Brandle JR., Johnson BB. and Akeson T. (1992) Field windbreaks; are they economical? J. Prod. Agric. 5 (3): 393 - 398.

Brandle JR. and Hintz DL. (1988) Windbreaks for the future. Agric. Ecosyst. Environ. 22 / 23: 593 - 596.

Brenner AJ., Jarvis PG. and Venderbelt RJ. (1995a) Windbreak - crop interactions in the Sahel: 1. Dependence of shelter on field conditions. Agricultural and Forest Meteorology 75 (4): 215 - 234. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Cable TT. and Cook PS. (1990) The use of windbreaks by hunters in Kansas. J. Soil Water Conserv. 45: 575 - 577. In: Brandle JR., Johnson BB. and Akeson T. (1992) Field windbreaks; are they economical? J. Prod. Agric. 5(3): 393 - 398.

Cleugh HA. and Hughes DE. (2000) The impact of shelter on crop microclimates: a synthesis of results from wind tunnel and field experiments. Unpublished.

Cleugh HA. (1998) Effects of windbreaks on airflow, microclimates and crop yields. Agrofor. Syst. 41: 55 - 84.

Davis JE. and Norman JM. (1988) Effects of shelter on plant water use. Agric. Ecosyst. Environ. 22 / 23: 393 - 402.

Dickey GL. (1988) Crop water use and water conservation benefits from windbreaks. Agric. Ecosyst. Environ. 22 / 23: 381 - 392.

Eastham J. and Rose CW. (1988) Pasture evapotranspiration under varying tree planting density in a agroforestry experiment. Agric. Water Management 15: 87 - 105.

Esterhuyse CJ. (1994) Agroforestry. In: Forestry Handbook. Van der Sijde HA. (ed.) pp. 802 - 817.

Fazli S. (1990) Financial analysis of selected shelterbelt systems in Pakistan. Pak. J. For. 40(3): 247 - 252. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Finch SJ. (1988) Field windbreaks: design criteria. Agric. Ecosyst. Environ. 22 / 23: 215 - 228.

Gillespie AR. (1989) Modelling nutrient flux and interspecies root competition in agroforestry plantings. Agrofor. Syst. 8: 257 – 265.

Hagen LJ. (1976) Windbreak design for optimum wind erosion control. Proc. Great Plains Agric. Counc. 78: 31 - 36. In: Banzhaf J., Leihner DE., Buerkert A. and Serafini PG. (1992) Soil tillage and windbreak effects on millet and cowpea: 1. Wind speed, evaporation and wind erosion. Agron. J. 84: 1056 - 1060

Haigh H. (1994) Farm forestry. In: Forestry Handbook. Van der Sijde HA. (ed.) pp. 828 - 840.

Heisler GM. and Dewalle DR. (1988) Effects of windbreak structure on wind flow. Agric. Ecosystems Environ., 22 / 23: 41 - 69.

Horvath GC., Knowles R. and Beall F. (1997b) A technology value assessment of shelterbelts in NZ. Scottish For. 51 (4): 232 - 237.

Howard SB., Ong CK., Black CR. and Khan AAH. (1997) Using sap flow gauges to quantify water uptake by tree roots from beneath the crop rooting zone in agroforestry systems. Agrofor. Syst. 35: 15 - 29.

Huxley PA., Pinney A., Akunda E. and Maraya P. (1994) A tree / crop interface orientation experiment with a *Grevillia robusta* hedgerow and maize. Agrofor. Syst. 26: 22 - 45.

Johnson RJ. and Beck MM. (1988) Influences of shelterbelts on wildlife management and biology. Agric. Ecosyst. Environ. 22 / 23: 301 - 335.

Kang BT., Grime H. and Lawson TL. (1985) Alley cropping sequentially cropped maize and cowpea with *Leuceana* on a sandy soil in Southern Nigeria. Plant and Soil 85: 267 - 277. In: Ssekabembe CK., Henderlong PR. and Larson M. (1994) Soil moisture relations at the tree / crop interface in black locust alleys. Agrofor. Syst. 25: 135 - 140.

Khan GS. and Ehrenreich JH. (1994) Effect of increasing distance from *Acacia nilotica* trees on wheat yield. Agrofor. Syst. 25: 23 - 29.

King M. and Sturrock JW. (1984). Shelter and the hill country environment. In: Finch S (1988) Field windbreaks: design criteria. Agric. Ecosyst. Environ. 22 / 23: 215 - 228.

Kiepe P. and Rao MR. (1994) Management of agroforestry for the conservation and utilization of land and water resources. Outlook on Agriculture 23 (1): 17 - 25. In: Sanchez PA. (1995) Science in agroforestry. Agrofor. Syst. 30: 5 - 55.

Kort J. (1988) The influence of field windbreaks on field and forage crops. Agric. Ecosyst. Environ. 22 / 23: 165 - 190

Kowalchuk TE. and De Jong E. (1995) Shelterbelts and their effect on crop yield. Can. J. Soil Sci. 75: 543 - 550.

Malik RS. and Sharma SK. (1990) Moisture extraction and crop yield as a function of distance from a row of *Eucalyptus tereticornis*. Agrofor. Syst. 12: 187 - 195.

McNaughton KG. (1988) Effects of windbreaks on turbulent transport and microclimate. Agric. Ecosyst. Environ. 22 / 23: 17 - 40.

Myburgh J. and Viljoen GK. (1979) Protection of deciduous fruit trees against wind. The Deciduous Fruit Grower, March. pp. 72 - 78.

Norton RL. (1988) Windbreaks: benefits to orchard and vineyard crops. Agric. Ecosystems Environ. 22 / 23: 205 - 213.

Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Ong CK., Black CR., Marshall FM. and Corlett JE. (1996) Principles of resource capture and utilisation of light and water. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Pienaar P. (1987) Wind protection in orchards: effect on growth, production and fruit quality. Deciduous Fruit Grower, August. pp. 291 - 295.

Puri S. and Bangarwa KS. (1992) Effects of tree yield of irrigated wheat crops in semi - arid regions. Agrofor. Syst. 20: 229 - 241.

Raupach, MRR. and Finnigan, JJ. (1997) The influence of topography on meteorological variables and surface-atmosphere interactions. J. Hydrol. 190: 182-165. In: Cleugh HA. and Hughes DE. (2000) The impact of shelter on crop microclimates: a synthesis of results from wind tunnel and field experiments. Unpublished.

Ritchie KA. (1988) Shelterbelt plantings in semi - arid areas. Agric. Ecosyst. Environ. 22 / 23: 425 - 440.

Rocheleau D., Weber F. and Field-Juma A. (1988) Agroforestry in dryland Africa. ICRAF. Nairobi, Kenya, 311 pp.

Sanchez PA. (1995) Science in agroforestry. Agrofor. Syst. 30: 5 - 55.

Schroth G. and Zech W. (1995) Root length dynamics in agroforestry with *Gliricidia sepium* as compared to sole cropping in the semi - deciduous rainforest zone of West Africa. Plant and Soil 170: 297 - 306. In: Cleugh HA., Miller JM. and Bohm M. (1998) Direct mechanical effects of wind on crops. Agrofor. Syst. 41: 83 - 112.

Smith DM. Jarvis PG. And Odongo JCW (1998) Management of windbreaks in the Sahal: the stategic implications of tree water use. Agrofor. Syst. 40: 83 – 96.

Srinivasalu and Jaganatham (1992) Microclimatic manipulation and performance of rainfed groundnut with crop shelterbelts. Madras Agricultural Journal 79 (10): 587 - 589. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Sturrock JW. (1972) Aerodynamic studies of shelterbelts in New Zealand: 2. Medium height to tall shelterbelts in mid Canterbury. NZ. J. Sci. 15; 113 - 140. In: Bird PR., Bicknell D., Bulman PA., Burke SJA., Leys JF., Parker JN., Van Der Sommen FJ. and Voller P. (1992). The role of shelter in Australia for protecting soils, plants and livestock. Agrofor. Syst. 20: 59 - 86.

Sturrock JW. (1969) Aerodynamic studies of shelterbelts in New Zealand: 1. Low to medium height shelterbelts in mid Canterbury. NZ. J. Sci. 12; 754 - 776. In: Bird PR., Bicknell D., Bulman PA., Burke SJA., Leys JF., Parker JN., Van Der Sommen FJ. and Voller P. (1992). The role of shelter in Australia for protecting soils, plants and livestock. Agrofor. Syst. 20: 59 - 86.

Sun D. and Dickinson GR. (1994) A case study of shelterbelt effect on potato (*Solanum tuberosum*) yield on the Atherton Tablelands in tropical north Australia. Agrofor. Syst. 25: 141 - 151

Van Asten P., Fermont A., Van Boom E. and Keet J. (1997) An investigation into the feasibilty of agroforestry for communal gardening in deprived communities of the Cape Flats; Interim report. University of the Western Cape, 68 pp.

Van Rensburg AD. (1973) Shelterbelts and windbreaks in South Africa. Department of Forestry; RSA. Pamphlet 118.

Van Noordwijk M. and Purnomosidhi P. (1995) Root architecture in relation to tree - soil crop interactions and root pruning in agroforestry. Agrofor. Syst. 30(1 - 2): 161 - 173.

Van Noordwijk M., Spek LY. and De Willigen P. (1994) Proximal diameters as predictors of total root system size for fractal branching models: Theory. Plant and Soil 164: 107 - 118.

Viljoen, GK. (1979). Evaluering van kunsmatige windskutte. Agrochemophysica 11: 21 - 26.

Williams J., Lyles L. and Langdale G. (1981) Soil erosion effects on soil productivity: A research perspective. J. Soil Water Conserv. 36: 82 - 90. In: Brandle JR., Johnson BB. and Akeson T. (1992) Field windbreaks; are they economical? J. Prod. Agric. 5(3): 393 - 398.

Zhang H., Brandle JR., Meyer GE. and Hodges L. (1995) A model to evaluate windbreak protection efficiency. Agrofor. Syst. 29: 191 - 200.

CHAPTER 2

AN INVESTIGATION OF THE VARIATION OF WIND SPEED, SOIL TEMPERATURE, AND SOIL MOISTURE CONTENT RELATIVE TO THE DISTANCE FROM WINDBREAKS IN THE WESTERN CAPE REGION OF SOUTH AFRICA

The purpose of this chapter was to investigate the microclimate variation in relation to the distance from windbreaks at the sites studied during 1999, at Villiersdorp Site 1 (ViS1) and Wolseley Site 1 (WoS1). The northern *Pinus radiata* windbreak at ViS1 was suspected to provide significant shelter from severe north-westerly winds in winter. The southern *Casuarina cunninghamiana* windbreak at WoS3 was suspected to provide shelter from severe south-easterly winds in spring and summer.

To record detailed data regarding wind speed, soil moisture, and soil temperature variation in relation to the windbreak, a CRX10 portable weather station operated on the leeward side of the windbreak to prevailing winds in the region. The weather station operated for a period of at least 2 months at each research site. The portable weather station was unavailable for use at the research sites established in 1998 due to technical problems.

1 VILLIERSDORP SITE 1 (ViS1)

1.1 Method

1.1.1 Wind speed, soil temperature, and soil moisture measurements

The northern *P. radiata* windbreak at ViS1 was suspected to provide significant shelter from severe north-westerly winds in winter. At ViS1, the weather station operated from 15 June to 14 September 1999 to obtain information concerning microclimate variation in relation to the distance from the northern windbreak. The windbreak had an effective height of 7.0 m. The unit was installed at 3.0 H to the lee (south) of the northern windbreak, from which the following sensors (connected by cables) extended across each research site:

1. The three wind speed sensors (anemometers) were placed at 1.5 m height. Wind speed measurements began on 15 June 1999, although the third anemometer did not produce meaningful data until further technical adjustments on 17 August 1999. From 15 June 1999 to 24 July 1999, one wind speed sensor was located at 1.0 H on the windward side, and the other was located at 3.0 H on the leeward side from the northern windbreak. From 24 July 1999 to 14 September 1999, the windward wind speed sensor was relocated to 11.0 H on the leeward side of the northern windbreak. The eventual functioning third wind sensor was located at 1.0 H on the leeward side of the northern windbreak from 23 August 1999 to 14 September 1999. Data were averaged over one hour, from 10-minute intervals.

2. The two soil temperature probes were located at 1.0 H to the windward side and 3.0 H to the leeward side of the northern windbreak, from 24 July to 14 September 1999. Probes were 20 cm below the soil surface. Data were sampled hourly.

3. The nine CS615 water content reflectometer (surface soil moisture content) probes were arranged across the site in a way that allowed for three replications. Therefore, three probes each were located at 1.0, 3.0, and 11.0 H to the lee of the northern windbreak, from 21 July to 14 September 1999. All CS615 measurements were made using the AM416 Relay Multiplexer. Probes were 20 cm below the soil surface. Data were averaged over one hour, from 10-minute intervals.

The portable weather station also recorded hourly sampled measurements of air temperature, evaporation, relative humidity (RH), and UV light.

Soil samples were collected at specific distances from the southern windbreak on 11 July 1999 to calibrate the data from the soil moisture probes. Samples were collected at 15 cm below the soil surface. Sampled soil was immediately sealed tightly in a labelled tin. Each tin was weighed, and weighed again following oven drying with lids loosened (at 100°C for 24 hours). Tins were then emptied and weighed. Calculations were made using the following formula:

$$\text{MC (\%)} = (\text{undried soil}^{\text{mass}} - \text{dried soil}^{\text{mass}}) / \text{dried soil}^{\text{mass}} \times 100$$

Data were also included from Department of Water Affairs and Forestry (DWAF) weather station at the nearby Chiltern Dam Wall. Data from this weather station included wind speeds, rainfall, temperature, evaporation, and relative humidity for the long term and the current year. Wind speeds from these stations were measured in km / day, so the level of information concerning brief yet severe winds during a day could easily be masked when averaged over the whole day and the whole month. At best, these wind speeds provided information concerning monthly trends.

1.1.2 Regional description

ViS1 was located 10 km west of Villiersdorp (longitude: 19°11′E, latitude 33°59′S, altitude: 330 m), on the "Mooi-Water" farm of Francois du Toit. Until approximately 1980, this farm retained its original fynbos (indigenous shrubs) whilst supporting small numbers of cattle. Plum and apple orchards have since been planted throughout the farm. Plate 1.1 in Section 3.2 $^{\text{Ch. 1}}$ illustrates the location of ViS1 in the Western Cape Region.

Table 1.1.1 shows the summarised long term and 1999 data collected from the "Chiltern Dam Wall" DWAF weather station, located 10 km south-west of ViS1. However, the Mooi-Water farm experienced a microclimate quite different to the climatic data presented by the DWAF weather station. The big difference between the locations was the absence of the prevailing south-easterly winds at the Mooi-Water farm during spring and summer, attributed to the presence of a nearby mountain to the south that effectively blocked out such winds. Winter and spring north-westerly winds were the prevailing winds at Mooi-Water, caused by wind being pushed through the Franschhoek Pass.

The climatic patterns at the DWAF weather station were more typical for the Western Cape Region. The average yearly long-term wind speed was 224.3 km / day, which was higher than any other project site. This was especially the case from May to December, attributed to the severe north-westerly winds in winter and spring, and also severe south-easterly winds in spring to summer. The average daily maximum temperature was 27.1°C for the hottest month (January) and the average daily minimum temperature for the coolest month (July) was 6.0°C. The site was in a temperate winter rainfall area, with June having the highest average monthly rainfall (177.9 mm), and January having the lowest average monthly rainfall (17.2 mm). Data for total evaporation and Relative Humidity (RH) are also included in Table 1.1.1.

Table 1.1.1 Long-term records and 1999 records of weather data recorded at the "Chiltern Dam Wall" weather station near Villiersdorp.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Long term av. wind speed (km / day)	247.4	246.5	211.8	176.9	170.2	206.5	227.8	218.3	233.1	240.3	252.4	260.0
1998 av. wind speed (km / day)	254.5	300.5	232.0	200.0	152.6	201.9	238.5	224.6	213.1	278.8	**	**
1998 av. max. wind speed (km / day)	518.5	675.9	401.2	628.9	406.9	709.4	668.8	504.0	520.2	801.9	**	**
Long term av. daily max. temp. (°C)	27.1	27.6	26.0	23.1	19.7	17.2	16.4	16.8	18.5	20.8	23.2	25.5
Long term av. daily minimum temp. (°C)	14.0	14.3	12.9	10.4	8.1	6.5	6.0	6.6	8.2	9.7	11.6	13.4
1998 av. daily maximum temp. (°C)	28.3	27.5	26.3	23.4	19.4	18.9	17.8	18.0	17.4	22.6	**	**
1998 av. daily minimum temp. (°C)	16.4	17.0	15.5	12.0	10.1	7.9	8.2	8.8	7.9	12.6	**	**
Long term av. total rain (mm)	17.2	19.8	19.6	61.4	127.6	177.9	161.0	143.7	72.1	49.8	28.1	29.8
1998 total rain (mm)	9.5	0.0	0.0	23.5	74.5	120.2	134.7	169.3	84.2	9.1	**	**
Long term av. total evaporation (mm)	230.2	190.0	161.8	99.8	67.2	53.2	57.6	74.3	95.3	145.2	177.3	211.1
1998 total evaporation (mm)	162.0	155.0	111.5	83.5	49.8	46.3	65.4	*55.0	69.0	128.6	**	**
Long term av. daily max. RH (%)	93.7	94.2	94.6	95.2	94.8	93.3	93.7	93.8	93.2	93.0	92.6	93.6
1998 av. daily max. RH (%)	97.1	96.5	95.8	93.6	94.6	90.6	90.1	88.7	91.5	90.5	**	**

* No evaporation measurements were made on 8 days of August 1999.

** Data for November and December 1999 were unavailable.

1.1.3 Site description

An aerial view of ViS1 is illustrated in Plate 1.1.1, and a profile view of the northern windbreak with adjoining crop strips (and weather station) is shown in Plate 1.2 in Section $3.2^{\text{Ch. 1}}$. This site had a *P. radiata* windbreak with an average effective height (H) of 7.0 m, adjoining the north and south borders of a vacant block of land. Distance between the two windbreaks was 170.0 m (24.2 H). The windbreaks were each orientated in a north-easterly direction. The 3-year old windbreak was double rowed and the trees were spaced 1.0 m apart from each other in a non-staggered pattern.

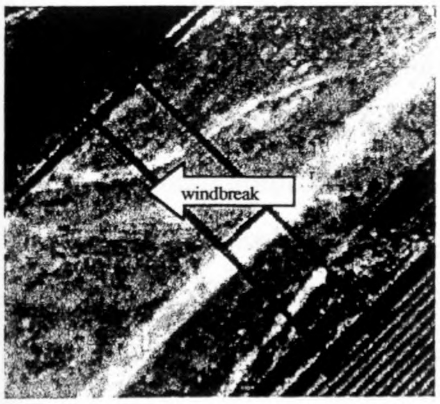

Plate 1.1.1 Aerial view of ViS1. Prevailing winds were north-westerly. Scale 1:4000.

This windbreak was pruned to a height of 2.0 m. Since gaps in the lower profile of the windbreak can cause serious damage to crops due to excessive turbulence (Rocheleau *et al.*, 1988), 50.0 m of netting of 40% porosity was necessary to seal gaps in the windbreak. Gaps were minimal following the installation of the netting. Access tracks of approximately 4.0 m width were present on the northern and southern side of the northern windbreak. Therefore, the minimum distance that the crops were established beside the northern windbreak was 5.0 m (0.7 H). Fynbos, not exceeding a height more than 1.5 m, existed between the two windbreaks and immediately to the north of the northern windbreak.

An initial soil investigation on 12 January 1999 provided an insight into the soil variations across the vacant block of land. This investigation involved a rapid collection of surface soil samples spaced at 20.0 m x 20.0 m from each other. The most homogenous 20.0 m wide section between both windbreaks was thereby selected for the site. The most southerly 40.0 m of vacant land (perpendicular to the northern windbreak) was excluded from the analysis as the soil in this area appeared much sandier compared to the more northerly areas.

Soil pits were excavated on 28 September 1999 at four central points running from north to south, and each to a depth of 0.8 to 1.0 m. Using Munsell colour codes (Munsell Color Co., 1975), each soil pit was described:

- Soil Pit 1 (0.5 H to the windward side of the windbreak). Classification: Tukulu 2110
    1. An orthic A horizon at 0 to 20 cm depth, about 5% clay content, a medium sand grade, and 10YR42 Munsell code.
    2. A neocutanic AB horizon at 20 to 50 cm depth, with about 7% clay content, a medium grade and 10YR31 Munsell code.
    3. An unconsolidated material with signs of wetness (BC horizon) at > 50 cm depth, with about 7% clay content, a medium sand grade, < 2% fine orange-yellowish brown mottling, and 25YR53 Munsell code.

- Soil Pit 2 (4.0 H to the leeward side of the windbreak). Classification: Pinedene 2100, transition to Constantia 1100
    1. An orthic A horizon at 0 to 20 cm depth, about 4% clay content, a medium sand grade, 10YR43 Munsell code.
    2. A yellow-brown apedal AB horizon at 20 to 30 cm depth, about 5% clay content, a medium grade, 10YR44 Munsell code.
    3. A yellow-brown apedal material with signs of wetness (BC horizon) at 30 to 60 cm depth, about 5% clay content, a medium sand grade, and 10YR58 Munsell code.
    4. An unspecified material with signs of wetness (C horizon) at > 60 cm depth, about 4% clay content, a medium sand grade, and 25YR66 Munsell code.

- Soil Pit 3 (5.0 H to the leeward side of the windbreak). Classification: Dundee (wet) 1210
    1. An orthic A horizon at 0 to 20 cm depth, about 4% clay content, a medium sand grade, and 25YR53 Munsell code.
    2. A stratified alluvium C1 horizon at 20 to 60 cm depth, about 4% clay content, a medium grade, < 2% medium (grey, yellow, and olive) mottling, very few (< 15%) coarse fragments (2 to 6 mm), and 25YR53 Munsell code.
    3. A stratified alluvium material with signs of wetness (C horizon) at > 60 cm depth, about 4% clay content, a coarse sand grade, 2 to 20% coarse (grey, yellow, and olive) mottling, many (50 to 90%) coarse fragments (25 to 75 mm), and 25YR53 Munsell code.

- Soil Pit 4 (12.8 H to the leeward side of the windbreak). Classification: Pinedene 2100, transition to Tukulu 2110.
    1. An orthic A horizon at 0 to 35 cm depth, about 4% clay content, medium sand grade, and 10YR41 Munsell code.
    2. A yellow-brown apedal B horizon at 35 to 55 cm depth, with 6% clay content, a medium grade, and 10YR46 Munsell code.

3. An unspecified material with signs of wetness (BC horizon) at > 55 cm depth, with 5% clay content, a medium sand grade, and 25YR76 Munsell code.

Munsell colour codes for surface soils at 1.0, 3.0, and 11.0 H were also described.

1.1.4 Experimental design

The general shape of the design was a 22.0 m wide vacant block extending 140.0 m (20.0 H) southwards and 10.0 m (1.4 H) northwards of the northern windbreak. An extra vacant strip was designated 5.0 to 8.0 m (1.0 H) to the northern (windward) side of the northern windbreak.

1.1.5 Windbreak porosity

Windbreak porosity was estimated using two photographs of 3.0 m x 3.0 m samples for each windbreak. Each image was scanned and then posturised by computer. The porosity was calculated using an image digitalisation programme that calculated the number of darker pixels compared to lighter pixels. The porosity of the two images from each windbreak was then averaged.

1.2 Results

1.2.1 ViS1 wind speed

Wind speed data were based on the averaged value during each hour, from samples taken at 10-minute intervals. Wind speed units were represented as m / s (1.0 m / s = 3.6 km / hr). The wind speed for each hour was the averaged value taken from six sampled wind speeds taken at 10-minute intervals. Due to this averaging over each hour, the magnitude of the wind speeds tended to be somewhat subdued compared to some of the momentary gusts of wind. For example, from the highly publicised gale force winds that occurred throughout the Western Cape Region from 16 October to 20 October

1999, exposed wind speeds recorded by the portable weather station at WoS3 ranged from 4.0 to 6.0 m / s. The averaged hourly wind speed of 4.0 m / s was therefore considered to be the minimum value of gale force winds.

Similarly, Van Gardingen and Grace (1991) noted that morphological responses of crops depended more on the intermittent and turbulent nature of wind than on the mean daily wind speed, and the exposure time necessary to induce these responses was possibly very low; in some cases 30 seconds or less. Therefore, sporadic high winds could have mechanical effects of far greater consequence than their relative frequency would indicate. Stem growth of *Phaseolus vulgaris* was reduced by 40% from 10 daily 4.7 m / s wind gusts, each lasting 10 seconds (Jaffe, 1976). Stem lengths of tomato plants, exposed to a 30-second gust / day for 35 days, were 42% smaller compared to the unshaken plants (Mitchell *et al.*, 1975).

Table 1.1.2 in Section 1.2.1.1 $^{\text{Ch. 2}}$ summarises the average hourly wind speeds at 1.0 H to the windward side and 3.0 H to the lee of the northern ViS1 windbreak. Table 1.1.3 in Section 1.2.1.2 $^{\text{Ch. 2}}$ summarises the average hourly wind speeds at 11.0 and 3.0 H to the lee of the northern ViS1 windbreak. Table 1.1.4 in Section 1.2.1.3 $^{\text{Ch. 2}}$ summarises the average hourly wind speed at 9.0, 3.0, and 1.0 H to the lee of the northern ViS1 windbreak.

North-westerly winds remained prevalent throughout each sampling period at ViS1. Interference from other winds resulted from mainly mild south-westerly and very mild south-easterly winds. The magnitude of the south-westerly winds increased in August and September 1999. By September 1999, stronger south-westerly, south-easterly, and easterly winds caused greater interference to the prevailing (but now less dominant) north-westerly winds. In October the north-westerly winds ceased being the prevalent wind, and south-easterly and easterly winds became dominant.

1.2.1.1 Sample period from 15 June 1999 to 23 July 1999

Table 1.1.2 Summary of the variation of average hourly wind speeds* at 1.0 H to the windward side (-1.0 H) and 3.0 H to the lee of the northern ViS1** windbreak.

wind speed (m/s) range (v).	hours	frequency (%)	wind speed at -1.0 H (m/s)	wind speed at 3.0 H (m/s)	wind speed reduction (m/s) at 3.0 H compared to -1.0 H	wind speed reduction (%) at 3.0 H compared to -1.0 H
9.0 < v < 10.0	1	0.3	9.00	6.83	2.17	24.11
8.0 < v < 9.0	2	0.6	8.95	6.87	2.08	23.26
7.0 < v < 8.0	10	2.8	7.39	5.40	1.98	26.97
6.0 < v < 7.0	24	6.7	6.57	4.75	1.82	27.74
5.0 < v < 6.0	24	6.7	5.49	3.82	1.67	30.38
4.0 < v < 5.0	27	7.5	4.44	3.01	1.43	32.17
3.0 < v < 4.0	43	11.9	3.49	2.30	1.19	34.06
2.0 < v < 3.0	47	13.1	2.48	1.64	0.84	33.86
1.0 < v < 2.0	47	13.1	1.59	1.02	0.57	35.97
0.0 < v < 1.0	135	37.5	0.59	0.71	-0.11	-19.30
all winds	360	100.0	2.46	1.85	1.18***	32.34***
north winds only	230	63.9	3.70	2.51	1.18	31.95

* Wind speed was recorded hourly. Each hourly unit was averaged from sample measurements every 10 minutes. Sampling period occurred from 15 June to 23 July 1999.

** Effective tree height (H) was 7.0 m. A negative tree height indicates a location on the windward side of the windbreak. A positive tree height indicates a location on the leeward side of the windbreak.

*** Totals for average wind speed reduction excluded wind speeds lower than1.0 m / s.

The highest wind speed during this sample period was 11.0 m / s, which occurred at midnight on 21 July 1999. Figure 1.1.1 shows the variation of all recorded wind speeds at 1.0 H to the windward side and 3.0 H to the lee of the northern ViS1 windbreak. Figure 1.1.2 shows the relationship of all recorded wind speeds at 3.0 H to the lee of the northern ViS1 windbreak, according to the corresponding sorted windward wind speeds. Figure 1.1.3 shows the correlation of all recorded wind speeds between 1.0 H to the windward side and 3.0 H to the lee, from the northern ViS1 windbreak. Figure 1.1.4 shows the correlation of wind speeds (from the northerly direction only) between 1.0 H to the windward side and 3.0 H to the lee, from the northern ViS1 windbreak.

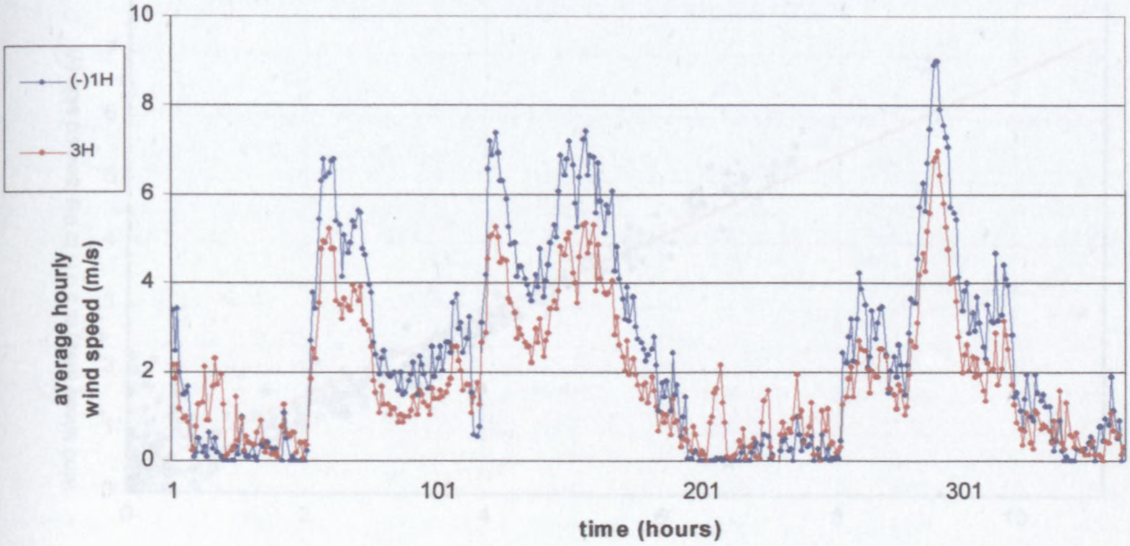

Figure 1.1.1 Variation of all recorded wind speeds at 1.0 H to the windward side and 3.0 H to the lee of the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. A negative H indicates a distance to the windward side of the windbreak. Sample period occurred from 15 June to 23 July 1999. Data points have been joined to enhance visual presentation.

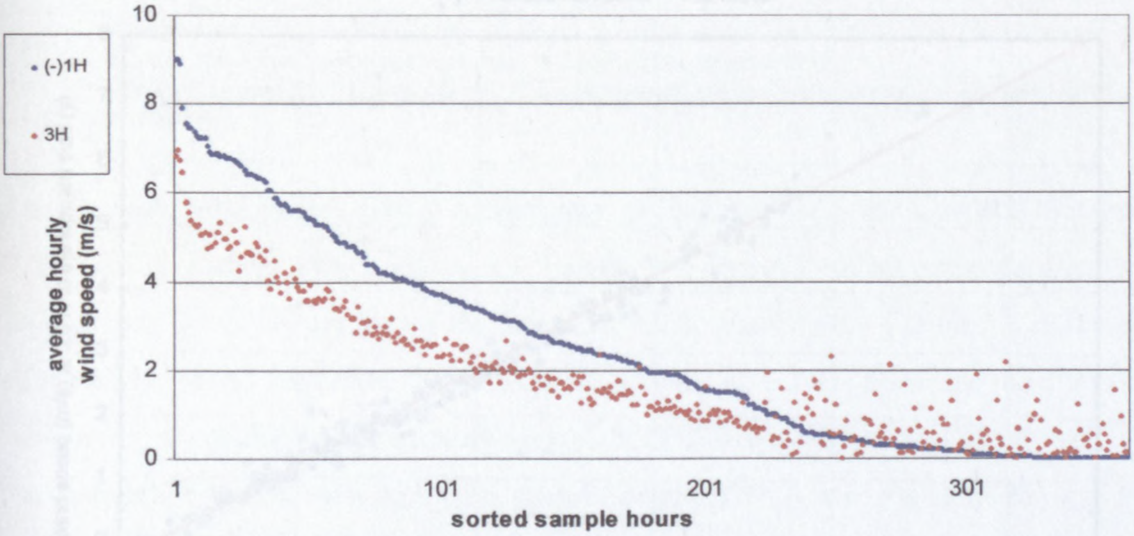

Figure 1.1.2 Relationship of all recorded wind speeds at 3.0 H to the lee of the northern *P. radiata* windbreak at ViS1, according to the corresponding sorted windward wind speeds. Effective tree height (H) was 7.0 m. A negative H indicates a distance to the windward side of the windbreak. Sample period occurred from 15 June to 23 July 1999.

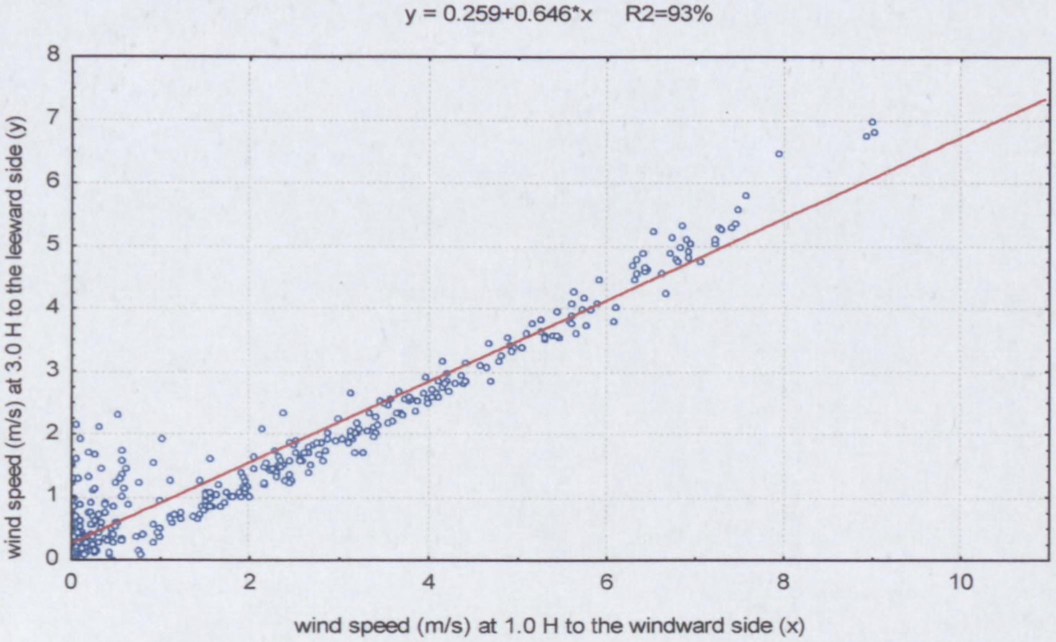

Figure 1.1.3 Correlation of all recorded wind speeds between 1.0 H to the windward side and 3.0 H to the lee, from the northern *P. radiata* windbreak. Effective tree height (H) was 7.0 m at ViS1. Sample period occurred from 15 June to 23 July 1999.

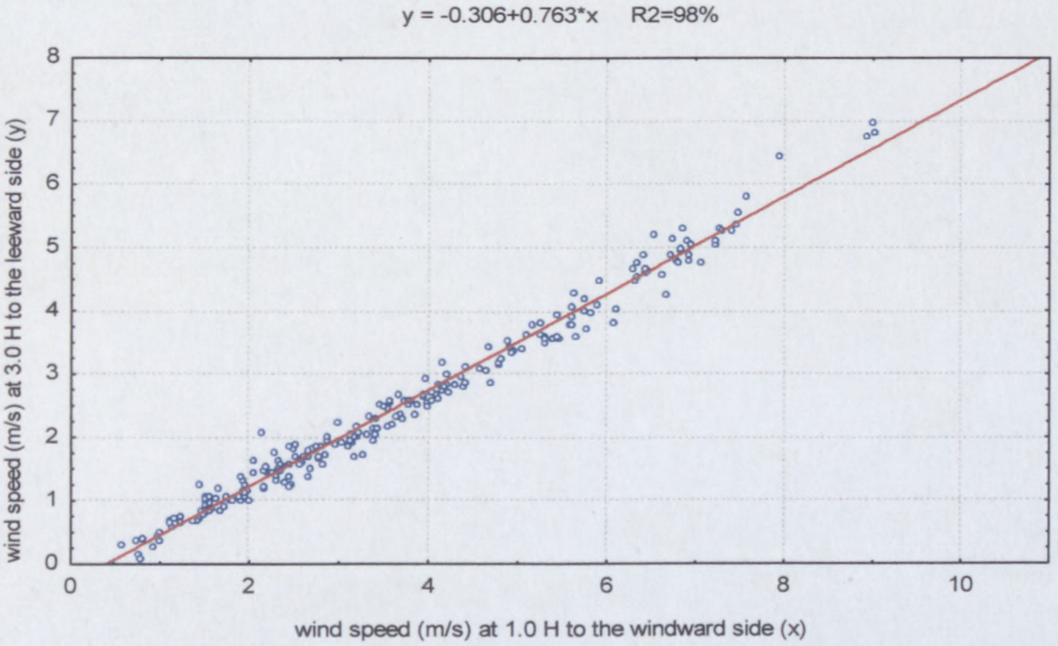

Figure 1.1.4 Correlation of wind speeds (from the northerly direction only) between 1.0 H to the windward side and 3.0 H to the lee, from the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. Sample period occurred from 15 June to 23 July 1999.

1.2.1.2 Sample period from 23 July to 14 September 1999

Table 1.1.3 Summary of the variation of average hourly wind speed* at 11.0 and 3.0 H to the lee of the northern ViS1** windbreak.

wind speed (m/s) range (v)	hours	frequency (%)	wind speed (m/s) at 11 H	wind speed (m/s) at 3 H	wind speed reduction (m/s) at 3 H compared to 11 H	wind speed reduction (%) at 3 H compared to 11 H
10.0 < v < 11.0	4	0.4	10.18	5.78	4.40	43.17
9.0 < v < 10.0	10	0.9	9.35	5.72	3.62	38.74
8.0 < v < 9.0	15	1.3	8.52	5.25	3.27	38.33
7.0 < v < 8.0	31	2.7	7.46	4.44	3.02	40.50
6.0 < v < 7.0	42	3.6	6.44	3.66	2.78	43.24
5.0 < v < 6.0	56	4.8	5.54	3.14	2.39	43.24
4.0 < v < 5.0	100	8.6	4.44	2.42	2.02	45.48
3.0 < v < 4.0	144	12.5	3.48	1.88	1.60	46.01
2.0 < v < 3.0	138	11.9	2.47	1.51	0.96	38.46
1.0 < v < 2.0	192	16.6	1.49	0.97	0.52	35.31
0.0 < v < 1.0	425	36.7	0.42	0.20	0.22	35.09
all winds	1157	100.0	2.44	1.40	1.04	38.72
northerly winds only	938	81.1	2.73	1.46	1.27	46.54

* Wind speeds were recorded hourly. Each hourly unit was averaged from sample measurements every 10 minutes. Sampling period occurred from 23 July to 13 September 1999

** Effective tree height (H) was 7.0 m. Both wind speed sensors were located on the leeward side of the windbreak.

The highest wind speed during this sample period was 10.6 m / s, which occurred at 22h00 on 13 August 1999. Figure 1.1.5 shows the variation of all recorded wind speeds at 11.0 and 3.0 H to the lee of the northern ViS1 windbreak. Figure 1.1.6 shows the relationship of all recorded leeward wind speeds at 3.0 H from the northern ViS1 windbreak, according to corresponding sorted 11.0 H wind speeds. Figure 1.1.7 shows the correlation of all recorded wind speeds between 11.0 and 3.0 H to the lee of the northern ViS1 windbreak. Figure 1.1.8 shows the correlation of wind speeds (from the northerly direction only) between 11.0 and 3.0 H to the lee of the northern ViS1 windbreak.

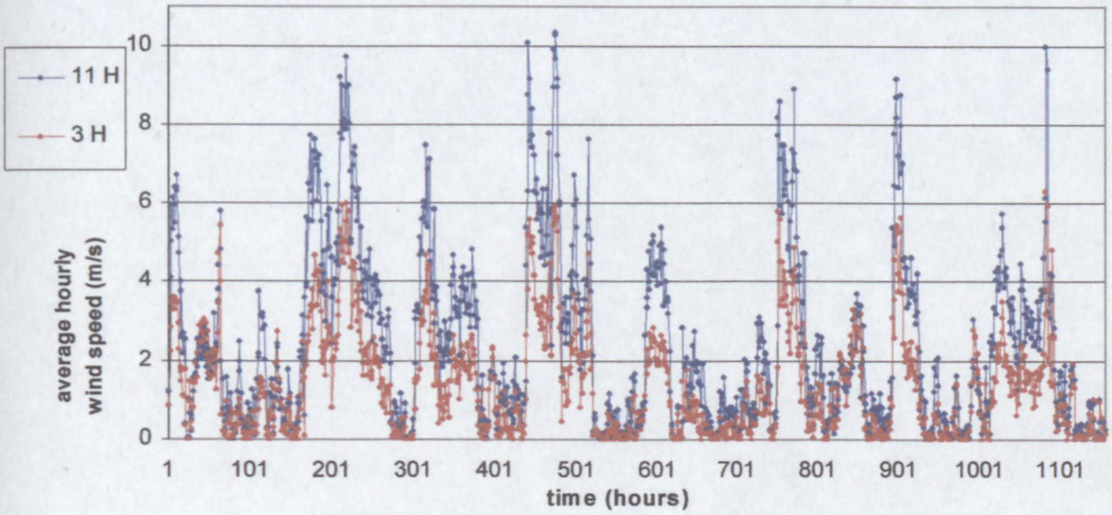

Figure 1.1.5 Variation of all recorded wind speeds at 11.0 and 3.0 H to the lee of the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. Sample period occurred from 23 July to 14 September 1999. Data points have been joined to enhance visual presentation.

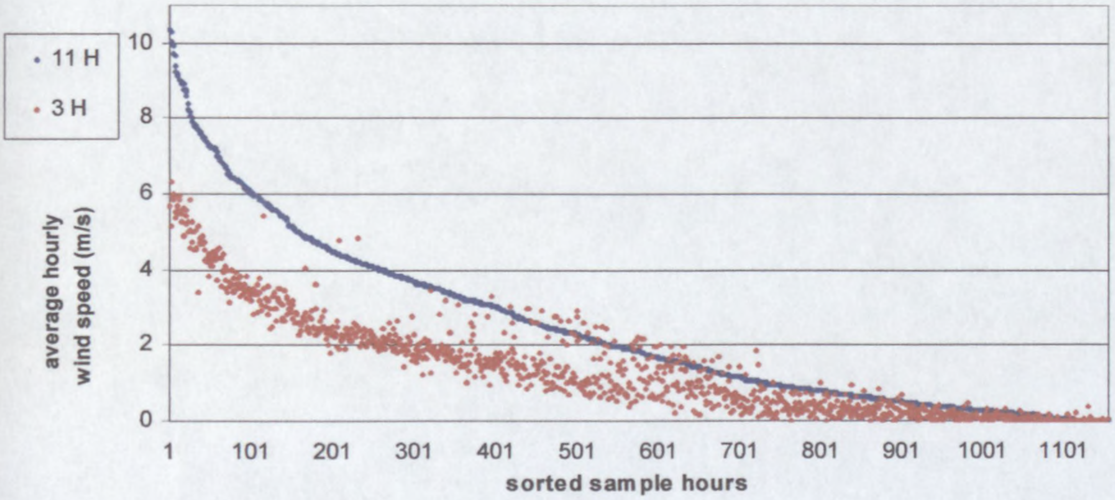

Figure 1.1.6 Relationship of all recorded leeward wind speeds at 3.0 H from the northern *P. radiata* windbreak at ViS1, according to corresponding sorted 11.0 H wind speeds. Effective tree height (H) was 7.0 m. Sample period occurred from 23 July to 14 September 1999.

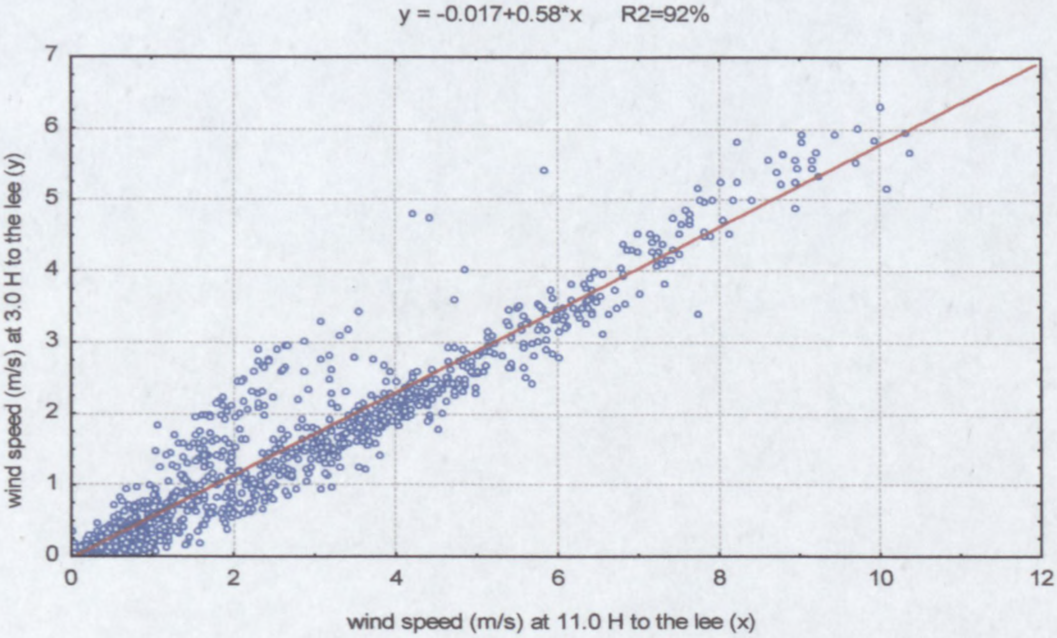

Figure 1.1.7 Correlation of all recorded wind speeds between 11.0 and 3.0 H to the lee of the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m at ViS1. Sample period occurred from 23 July to 14 September 1999.

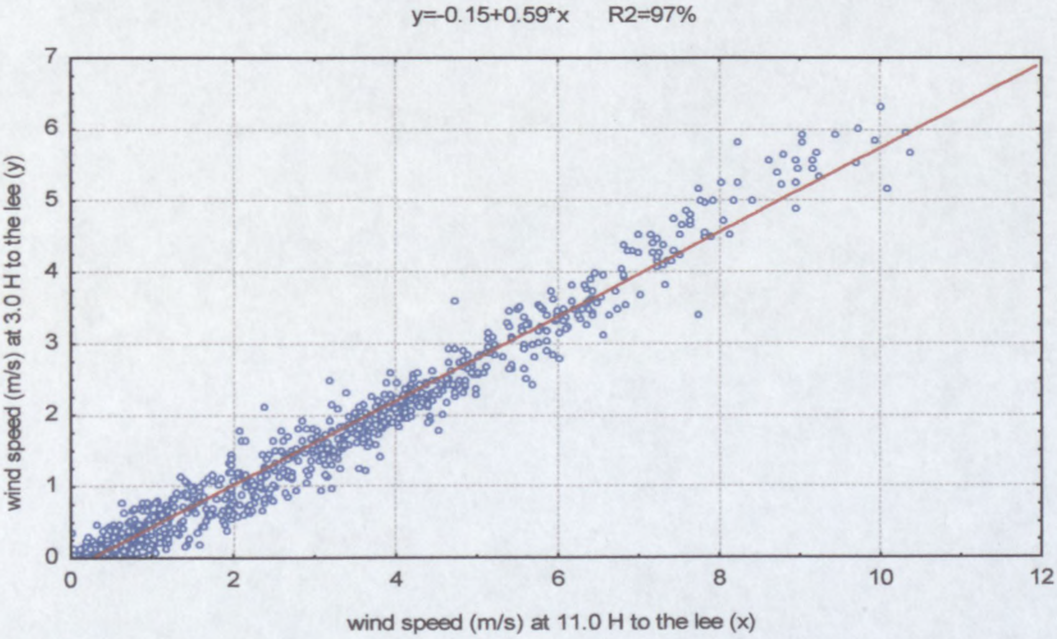

Figure 1.1.8 Correlation of wind speeds (from the northerly direction only) between 11.0 and 3.0 H to the lee of the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m at ViS1. Sample period occurred from 23 July to 14 September 1999.

1.2.1.3 Sample period from 18 August to 14 September 1999

Table 1.1.4 Summary of the variation of average hourly wind speed* at 11.0, 3.0, and 1.0 H to the lee of the northern ViS1** windbreak.

wind speed (m/s) range (v)	hours	frequency (%)	wind speed (m/s) at 11 H	wind speed (m/s) at 3 H	wind speed (m/s) at 1 H	wind speed reduction (m/s) at 3 H compared to 11 H	wind speed reduction (m/s) at 1 H compared to 11 H	wind speed reduction (%) at 3 H compared to 11 H	wind speed reduction (%) at 1 H compared to 11 H
10.0 < v < 11.0	1	0.2	10.00	6.33	4.69	3.67	5.31	36.69	53.09
9.0 < v < 10.0	2	0.4	9.29	5.70	4.78	3.59	4.50	38.63	48.49
8.0 < v < 9.0	7	1.3	8.49	5.41	4.99	3.08	3.50	36.26	41.23
7.0 < v < 8.0	9	1.7	7.40	4.35	4.20	3.05	3.19	41.22	43.18
6.0 < v < 7.0	12	2.3	6.50	3.75	3.77	2.76	2.73	42.37	41.98
5.0 < v < 6.0	9	1.7	5.62	3.24	3.21	2.38	2.41	42.28	42.81
4.0 < v < 5.0	31	5.9	4.42	2.43	2.48	1.99	1.94	45.06	43.82
3.0 < v < 4.0	51	9.7	3.45	1.94	1.90	1.51	1.55	43.78	44.84
2.0 < v < 3.0	66	12.6	2.49	1.42	1.50	1.07	0.99	42.99	39.66
1.0 < v < 2.0	109	20.8	1.52	0.99	0.91	0.53	0.61	34.86	40.40
0.0 < v < 1.0	228	43.4	0.44	0.19	0.28	0.25	0.16	56.30	36.03
all winds	525	100.0	1.96	1.12	1.14	0.83	0.82	42.67	41.81
north winds only	389	74.1	2.28	1.19	1.24	1.09	1.04	47.82	45.60

* Wind speeds were recorded hourly. Each hourly unit was averaged from sample measurements every 10 minutes. Sampling period occurred from 18 August to 13 September 1999

** Effective tree height (H) was 7.0 m. All wind speed sensors were located on the leeward side of the windbreak.

The highest wind speed during this sample period was 10.2 m / s, which occurred at 08h00 on 11 September 1999. Figure 1.1.9 shows the variation of all recorded wind speeds at 11.0, 3.0, and 1.0 H to the lee of the northern ViS1 windbreak. Figure 1.1.10 shows the relationship of all recorded wind speeds at 3.0 and 1.0 H to the lee of the northern ViS1 windbreak, according to corresponding sorted 11.0 H wind speeds. Figure 1.1.11 shows the correlation of all recorded wind speeds at 11.0 H with that at 3.0 and 1.0 H to the lee of the northern ViS1 windbreak. Figure 1.1.12 shows the correlation of wind speeds (from the northerly direction only) at 11.0 H with that at 3.0 H and 1.0 H to the lee of the northern ViS1 windbreak.

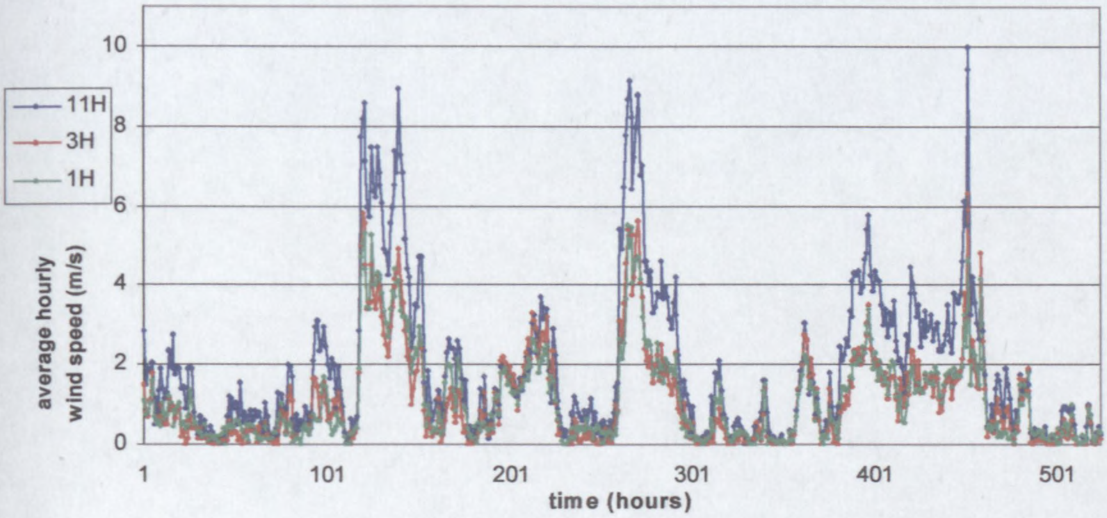

Figure 1.1.9 Variation of all recorded wind speeds at 11.0, 3.0, and 1.0 H to the lee of the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. Sample period occurred from 18 August to 14 September 1999. Data points have been joined to enhance visual presentation.

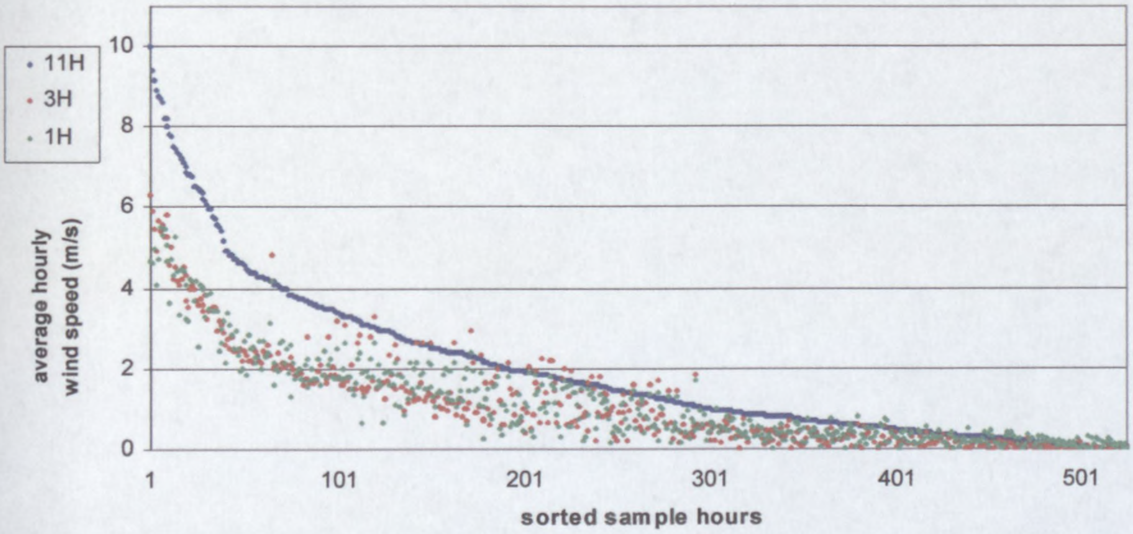

Figure 1.1.10 Relationship of all recorded wind speeds at 3.0 and 1.0 H to the lee of the northern *P. radiata* windbreak at ViS1, according to corresponding sorted 11.0 H wind speeds. Effective tree height (H) was 7.0 m. Sample period occurred from 18 August to 14 September 1999.

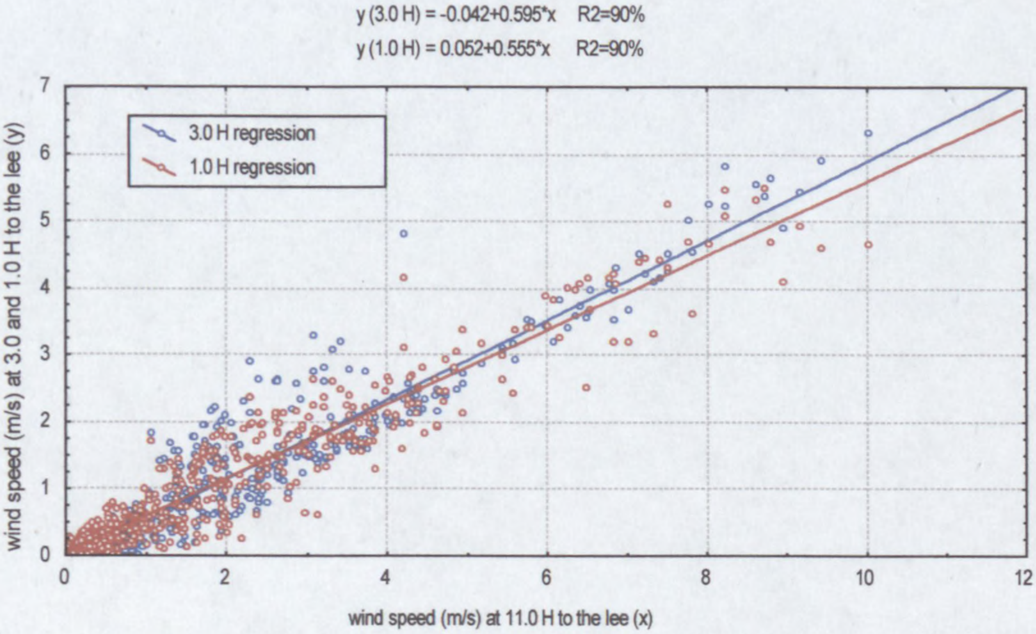

Figure 1.1.11 Correlation of all recorded wind speeds at 11.0 H with that at 3.0 and 1.0 H to the lee of the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. Sample period occurred from 18 August to 14 September 1999.

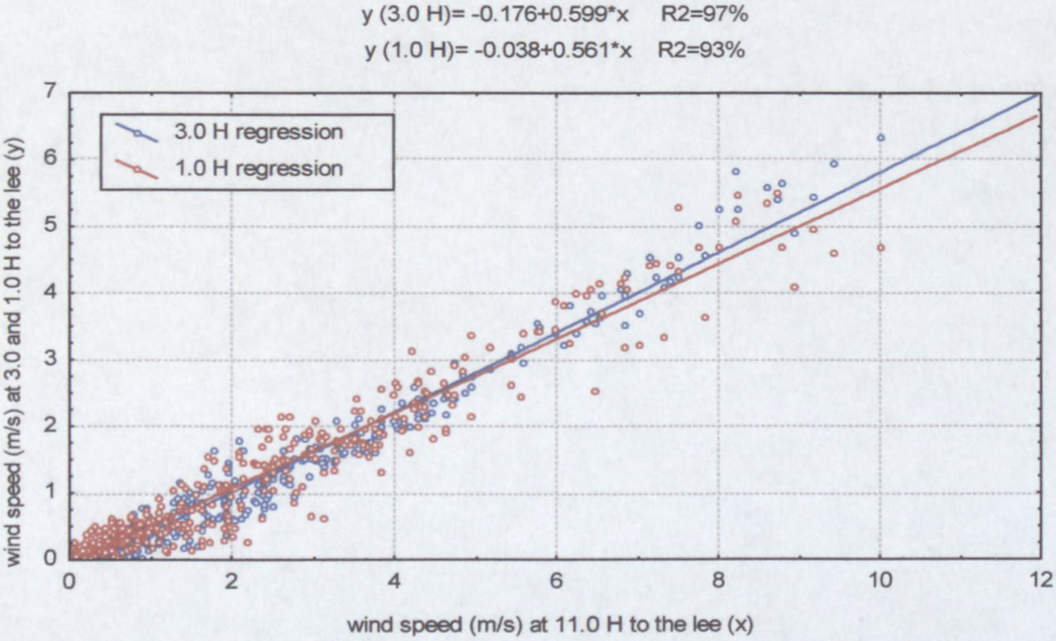

Figure 1.1.12 Correlation of wind speeds (from the northerly direction only) at 11.0 H with that at 3.0 H and 1.0 H to the lee of the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. Sample period occurred from 18 August to 14 September 1999.

1.2.2 ViS1 soil temperature

Soil temperature samples were taken once every hour. Figure 1.1.13 shows the variation of soil temperature at 1.0 H to the windward side and 3.0 H to the lee of the northern ViS1 windbreak. Corresponding wind speeds at 11.0 H to the lee are also shown.

Figure 1.1.14 shows the difference of soil temperatures between 1.0 H to the windward side and 3.0 H to the lee of the northern ViS1 windbreak. A positive temperature difference indicates a higher temperature at 3.0 H, compared to the windward side. Corresponding wind speeds at 11.0 H to the lee are also shown. These wind speeds have been transformed to their respective square roots.

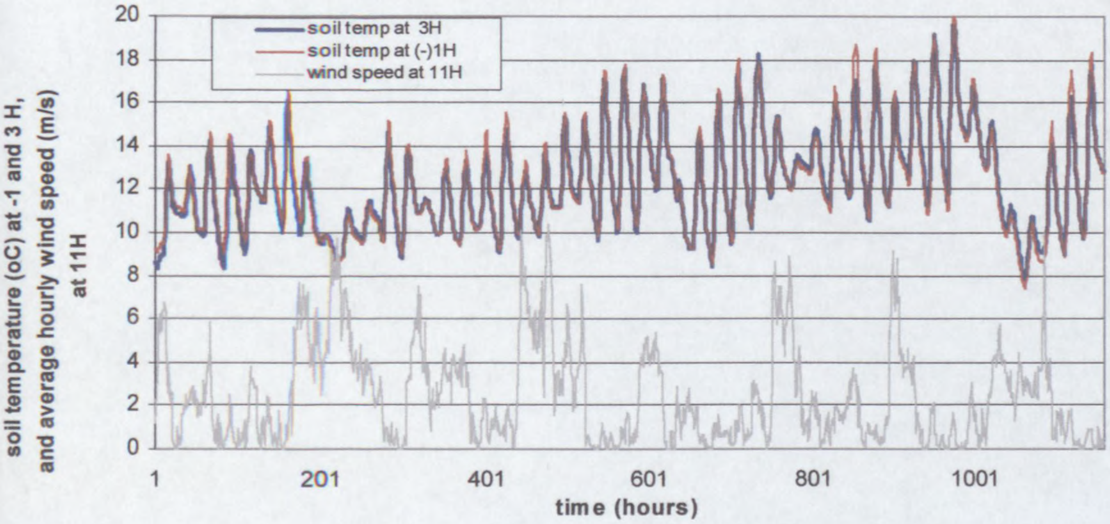

Figure 1.1.13 Variation of soil temperature at 1.0 H to the windward side and 3.0 H to the lee of the northern *P. radiata* windbreak at ViS1 (and the corresponding wind speeds at 11.0 H). Effective tree height (H) was 7.0 m. Sample period occurred from 24 July to 14 September 1999. Data points have been joined to enhance visual presentation.

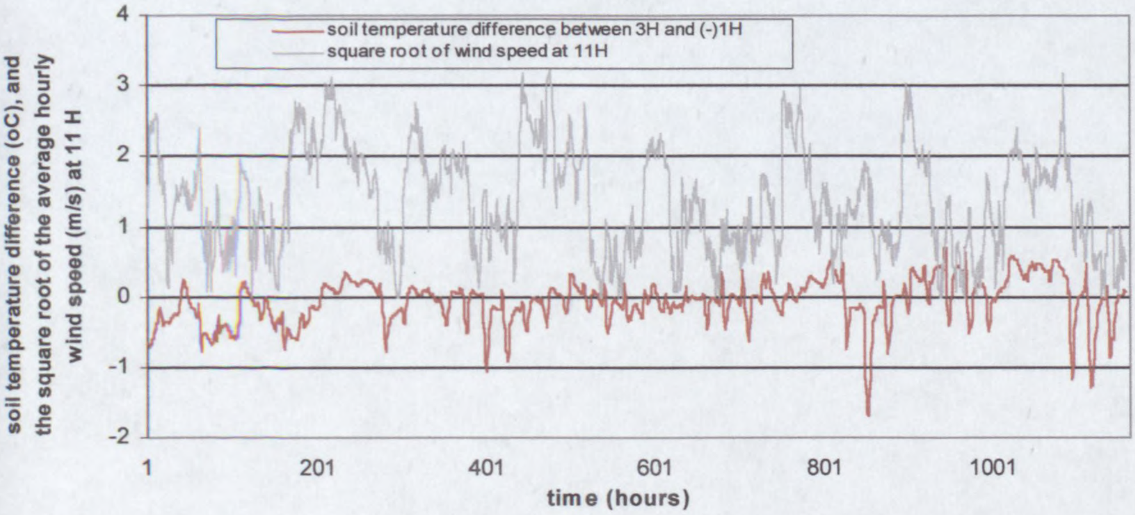

Figure 1.1.14 Difference of soil temperatures between 1.0 H to the windward side and 3.0 H to the lee of the northern *P. radiata* windbreak at ViS1. A positive temperature difference indicates a higher temperature at 3.0 H, compared to the windward side. Corresponding wind speeds at 11.0 H to the lee are also shown. Wind speeds have been transformed to their respective square roots. Effective tree height (H) was 7.0 m. Sample period occurred from 24 July to 14 September 1999. Data points have been joined to enhance visual presentation.

1.2.3 ViS1 soil moisture

Soil moisture data were based on the averaged value during each hour, from samples taken at 10-minute intervals. Figure 1.1.15 shows the averaged variation of soil moisture content at 11.0, 3.0, and 1.0 H to the lee of the northern ViS1 windbreak. A consistent dark greyish brown 10YR42 wet Munsell colour code (Munsell Color Co., 1975) was described for the soils at each location.

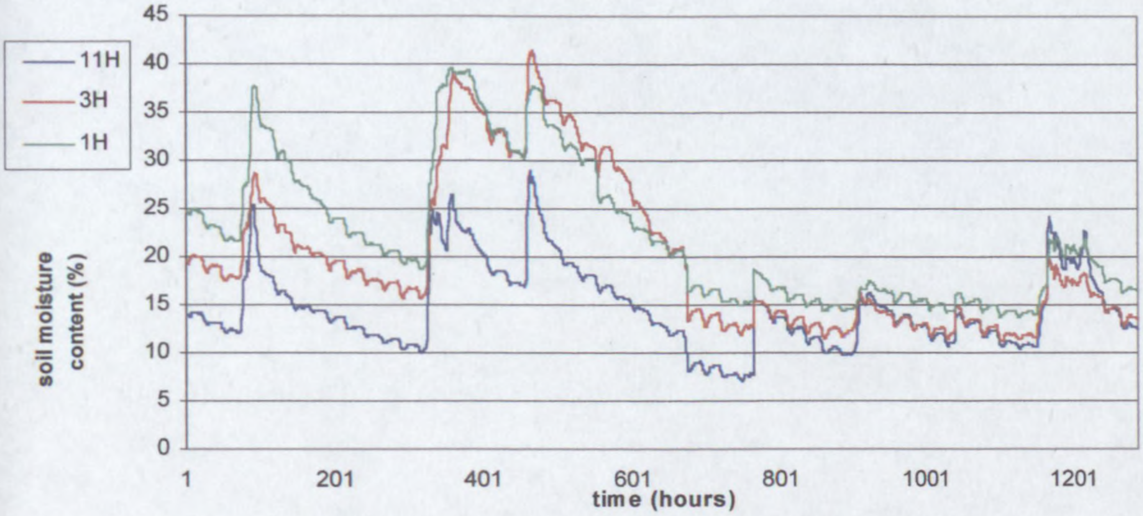

Figure 1.1.15 Averaged variation of soil moisture content at 11.0, 3.0, and 1.0 H to the lee of the northern *P. radiata* windbreak at ViS1. Data from 11.0 and 1.0 H were averaged from 3 soil probes. At 3.0 H, one of the probes failed to function so data at this distance were represented by 2 soil probes only. A sudden drop in soil moisture content at approximately 670 hours was caused by adjustments of soil probes during site maintenance procedures. Effective tree height (H) was 7.0 m. Sample period occurred from 21 July to 14 September 1999. Data points have been joined to enhance visual presentation.

1.3 Discussion

1.3.1 ViS1 wind speed

1.3.1.1 Sample period from 15 June to 23 July 1999

During the first sampling period at ViS1, one wind sensor was located at 1.0 H to the windward side of the windbreak (-1.0 H), and the other wind sensor was located at 3.0 H to the leeward side of the windbreak (Table 1.1.2 and Figure 1.1.1 in Section 1.2.1.1 $^{\text{Ch. 2}}$).

Excluding wind speeds below 1 m / s (for reasons explained in the following paragraph), the average general wind speed at 1.0 H to the windward side was 2.5 m / s, compared to 1.9 m / s at 3.0 H to the lee. Therefore, the windbreak resulted in a 32% wind speed reduction in the more sheltered 3.0 H zone, relative to the more exposed wind speed on the windward side. Northerly winds occurred for 64% of the sampling period, indicating that these winds were severe and potentially damaging to crops.

Very mild southerly winds reversed the shelter effect at wind speeds below 1 m / s, resulting in higher wind speeds at the wind sensor located at 3.0 H to the lee relative to those on the windward side of the windbreak. When these mild southerly winds were excluded, the average wind speed at 1.0 H to the windward side was 3.7 m / s, compared to 2.5 m / s at 3.0 H to the lee. The exclusion of southerly winds had little effect on the wind speed reduction levels, compared to those described in the previous paragraph. Therefore, the southerly winds had a negligible impact on the general shelter effect.

From Figure 1.1.1, the mild southerly winds were mainly represented by two 40 to 50 hour periods when the wind speeds at 3.0 H to the lee tended to be higher than wind speeds at 1.0 H to the windward side. For the remainder of the 361-hour sample period, northerly winds ensured a pronounced shelter effect at 3.0 H to the lee, relative to those on the windward side. The pronounced general shelter effect at higher exposed wind speeds is further illustrated in Figure 1.1.2, which shows the relationship of all recorded wind speeds at 3.0 H, according to corresponding sorted windward wind speeds. The interference of the mild southerly winds are indicated by the lack of trend for wind speeds below 1 m / s at 3.0 H.

Figure 1.1.3 illustrates a high correlation ($r^2 = 93\%$) between wind speeds at both anemometers. However, the mild southerly winds interfered with the regression of general shelter effect for which the ViS1 windbreak was designed. To improve the correlation of the shelter effect, the mild southerly winds (contaminating data comprising 36% of the total data) were excluded in Figure 1.1.4 to produce an improved regression ($r^2 = 98\%$) and subsequently an improved predictive equation. The subsequent regression equation was linear:

$y = -0.306 + 0.763x$,

where x = wind speed at 1.0 H to the windward side, and
y = wind speed at 3.0 H to the leeward side (if $y < 0$, then $y = 0$).

As wind speed for each hour was the averaged value taken from six sampled wind speeds taken at 10-minute intervals, the magnitude of the recorded wind speeds were subdued compared to some of the momentary gusts of wind. From the gale force winds that occurred throughout the Western Cape Region from 16 October to 20 October 1999, exposed wind speeds recorded by the portable weather station at WoS3 ranged from 4.0 to 6.0 m / s. The averaged hourly wind speed of 5.0 m / s was therefore considered to be gale force

According to this improved regression equation, gale force winds of 5.0 m / s at 1.0 H to the windward side would be reduced to 3.5 m / s at 3.0 H to the lee. Therefore, for a northerly wind for which the ViS1 windbreak was designed, a 5.0 m / s wind was confidently predicted to be reduced by 30% in the sheltered zone, for this particular sampling period.

The DWAF weather station located near the site recorded typical average monthly wind speeds throughout 1999. High average maximum wind speeds during the winter and spring period increased the potential of a significant shelter effect being produced at this site.

1.3.1.2 Sample period from 23 July to 14 September 1999

During the second sampling period, wind sensors were located at 3.0 and 11.0 H to the leeward side of the windbreak (Table 1.1.3 and Figure 1.1.5 in Section 1.2.1.2$^{\text{Ch. 2}}$). The average wind speed at 11.0 H was 2.4 m / s, compared to 1.4 m / s at 3.0 H. Therefore, the windbreak resulted in a 39% wind speed reduction at 3.0 H, relative to the more exposed 11.0 H. Northerly winds occurred for 81% of the sampling period, indicating that these winds were prevalent and potentially damaging to crops.

A pronounced leeward shelter effect was further indicated when the wind speeds at 11.0 H were sorted in descending order according to the corresponding wind speeds at 3.0 H, shown in Figure 1.1.6. Some interference to the general trend, attributed to mainly south-westerly winds, occurred between approximately 1.0 to 3.0 m / s in the exposed zone. When these southerly winds were excluded, the average wind speed at 3.0 H was 1.4 m / s, compared to 2.7 m / s at 11.0 H. The exclusion of southerly winds increased the wind speed reduction level from 39 to 47%, indicating that the southerly winds reduced the effectiveness of the general shelter effect by 8%. This might necessitate the requirement of a series of parallel windbreaks at ViS1 to provide maximum shelter from both north-westerly winds and south-westerly winds.

Figure 1.1.7 illustrates a high correlation ($r^2 = 92\%$) between wind speeds at both anemometers. As observed for the previous sampling period, southerly winds interfered with the regression of general shelter effect for which the ViS1 windbreak was designed. This was indicated by a faint secondary trend that deviated above the general trend.

To improve the correlation of the shelter effect, the mild southerly winds (contaminating data comprising 19% of the total data) were excluded in Figure 1.1.8 to produce an improved regression ($r^2 = 97\%$) and subsequently an improved predictive equation. The subsequent regression equation was linear:

$$y = -0.150 + 0.590x,$$

where x = wind speed at 11.0 H to the lee, and

y = wind speed at 3.0 H to the lee (if $y < 0$, then $y = 0$).

As wind speed for each hour was the averaged value taken from six sampled wind speeds taken at 10-minute intervals, the magnitude of the recorded wind speeds were subdued compared to some of the momentary gusts of wind. As explained in the previous sampling period in Paragraph 6 of Section 1.3.1.1 $^{\text{Ch. 2}}$, the averaged hourly wind speed of 5 m / s was deduced to be gale force.

According to this improved regression equation, gale force winds of 5.0 m / s at 11.0 H would be reduced to 2.8 m / s at 3.0 H to the lee. Therefore, for a northerly wind for which the ViS1 windbreak was designed, a 5.0 m/s wind was confidently predicted to be reduced by 44% in the sheltered zone, for this particular sampling period.

1.3.1.3 Sample period from August to 14 September 1999

This sample period took place within the previous sample period. The reason for focusing on this particular section of the previous sample period was to provide a more detailed analysis of an extra wind sensor located at 1.0 H that became operational on 17 August 1999. Wind sensors were located to the leeward side of the windbreak. The other two wind sensors were located at 11.0 and 3.0 H, as in the previous sampling period (Table 1.1.4 in Figure 1.1.9 in Section 1.2.1.3 $^{\text{Ch. 2}}$). The general shelter effect is further illustrated in Figure 1.1.10, which illustrates the relationship of leeward wind speeds at 3.0 and 1.0 H according to corresponding sorted wind speeds at 11.0 H. The lower average wind speeds during this sample period were lower compared to the two previous sampling periods, indicating that prevalent north-westerly winds were becoming more subdued. This reflected a typical seasonal trend. The regional DWAF weather station also recorded a decrease in averaged maximum monthly wind speeds in August and September 1999.

The average hourly wind speed at 11.0 H was 2.0 m / s, compared to 1.1 and 1.1 m / s at 3.0 and 1.0 H to the lee respectively. In relation to 11.0 H, the level of wind speed reduction at 3.0 and 1.0 H was 43 and 42% respectively. Northerly winds occurred for

74% of the sampling period, indicating that these winds were prevalent and potentially damaging to crops.

Interference to the general trend was attributed to mainly south-westerly winds, as stated for the previous sample period. When these southerly winds were excluded, the average wind speed at both 3.0 and 1.0 H was 1.2 m / s, compared to 2.3 m / s at 11.0 H. The exclusion of southerly winds increased the wind speed reduction level from 43 to 49% at 3.0 H and from 42 to 46% at 1.0 H. Therefore, the southerly winds reduced the effectiveness of the general shelter effect by 6 and 4% at 3.0 and 1.0 H respectively. As stated in the previous sample period (previous section), this reduction in the shelter effect may necessitate the requirement of a series of parallel windbreaks at ViS1 to provide maximum shelter from both north-westerly winds and south-westerly winds.

Figure 1.1.11 illustrates an equally high correlation between wind speeds at 11.0 H and those at 3.0 and 1.0 H ($r^2 = 90\%$ for both sheltered locations). As observed for the previous sampling periods at ViS1, southerly winds interfered with the regression of general shelter effect for which the windbreak was designed. This was indicated by a faint secondary trend that deviated above the general trend.

To improve the correlation of the shelter effect, the mild southerly winds (contaminating data comprising 26% of the total data) were excluded in Figure 1.1.12 to produce improved correlations between wind speeds at 11.0 H and those at 3.0 ($r^2 = 97\%$) and 1.0 H ($r^2 = 93\%$). The regression equations were linear:

For 3.0 H, $y = -0.176 + 0.599x$,

For 1.0 H, $y = -0.038 + 0.561x$,

where x = wind speed at 11.0 H to the lee, and

y = wind speed at 3.0 or 1.0 H to the lee (if $y < 0$, then $y = 0$).

As wind speed for each hour was the averaged value taken from six sampled wind speeds taken at 10-minute intervals, the magnitude of the recorded wind speeds were subdued compared to some of the momentary gusts of wind. As explained in the first sampling period in Paragraph 6 of Section 1.3.1.1 $^{\mathrm{Ch.\ 2}}$, the averaged hourly wind speed of 5 m / s was deduced to be gale force.

According to this improved regression equation, gale force winds of 5.0 m / s at 11.0 H would be reduced to 2.8 m / s at both 3.0 and 1.0 H. Therefore, for a northerly wind for which the ViS1 windbreak was designed, a 5.0 m/s wind was confidently predicted to be reduced by 56% in the sheltered zone (1.0 to 3.0 H), for this particular sampling period. The similarly low wind speeds at 1.0 and 3.0 H to the lee indicated that the maximum level of shelter extended to 3.0 or 4.0 H to the lee.

Other investigations similarly reported that maximum wind speed reductions occurred in the zone ranging from 3.0 to 6.0 H (Cleugh and Hughes, 2000; Cleugh, 1998; Sun and Dickinson, 1997; Hodges and Brandle, 1996; Bird, 1988, Ujah and Adeoye, 1984). The area of maximum shelter was estimated by Nuberg (1998) to range from 4.0 and 12.0 H. From wind tunnel tests, Tibke (1988) reported that maximum shelter extended to 9.0 H.

Compared to that at 3.0 H, the shelter effect at 1.0 H became more pronounced when exposed wind speeds exceeded 7.0 m / s. This may suggest that the ViS1 windbreak displayed low levels of wind jetting through its structure during periods of high winds. The consistent porosity produced by the shade netting was more likely to have been the dominant factor causing this reduction of turbulence, rather than any influence by the windbreak.

A windward shelter effect was also evident. The reduction of the effectiveness of the shelter effect due to southerly winds at 1.0 H was 2% less than that at 3.0 H. The improved regression equations in Figure 1.1.12 also had less impact on the r^2 value for the 1.0 H data, compared to the 3.0 H data. This was attributed to a less pronounced secondary trend caused by the southerly winds at 1.0 H, compared to 3.0 H. Effective windbreaks provide shelter for up to 5.0 H on the windward side (Cleugh and Hughes, 2000; Haigh, 1994), although a smaller windward range of 1.0 to 3.0 H has also been suggested (Hodges and Brandle, 1996; Pretzechel *et al.*, 1991; Pienaar, 1987).

1.3.2 ViS1 soil temperature

At ViS1, soil temperature probes were located at 1.0 H to the windward side and 3.0 H to the lee, from 24 August to 14 September 1999. Readings were recorded once every hour. There was very little soil temperatures difference between these locations, as shown in Figures 1.1.12 and 1.1.13 in Section 1.2.2$^{\text{Ch. 2}}$.

However, the windward location cannot be considered a fully exposed zone. In fact, 1.0 H to the windward side was potentially highly sheltered at crop height due to the 1.0 m high fynbos at the northern boundary of the cleared area. Considering that the soil temperature probe was only 3.0 m from the fynbos 'windbreak', the soil temperature probe was well within the sheltered zone attributed by the fynbos. The potential extent of the fynbos shelter effect was 6.0 to 10.0 m. The fynbos shelter effect at crop level was not indicated by the windward wind speed data in Section 1.3.1.1 $^{\text{Ch. 2}}$ because the anemometer unit was positioned at 1.5 m above the ground, thereby being beyond the influence of the fynbos.

1.3.3 ViS1 soil moisture

Given that the soils at each of these locations were similar (indicated by the Munsell colour codes described in Section 1.2.3 $^{\text{Ch. 2}}$), then variations in soil moisture content were directly attributed to a shelter effect from the windbreak. Soil probes were located at 1.0, 3.0, and 11.0 H to the lee of the northern ViS1 windbreak from 21 July to 14 September 1999 (Figure 1.1.14 in Section 1.2.2 $^{\text{Ch. 2}}$). Soil moisture data were based on the averaged value during each hour, from samples taken at 10-minute intervals.

The entire growing period at ViS1 occurred when soil moisture levels were assumed to be unlimiting. This assumption was based firstly on the sufficiently high soil moisture content (generally 10 to 12%), and secondly on the regular periods of recharge due to rains (indicated by the rapid increases in soil moisture content). Levels of recharge became less after approximately 700 hours, but continued nonetheless.

A high amount of regular recharge and subsequent surface runoff from 350 to 680 hours appears to have caused the high soil moisture contents at both 3.0 and 1.0 H to at a similar level and to fluctuate excessively. By excluding this period of soil saturation, a clearer indication of a possible soil-moisture conservation effect emerged.

Compared to 3.0 H (and 1.0 H), the soil moisture content at 11.0 H tended to decrease more rapidly. This deviation of soil moisture content between 3.0 and 11.0 H, following periods of recharge, indicated a soil-moisture conservation effect. Perhaps a sampling period with less rain might have produced a less interrupted trend of this soil-moisture conservation effect.

Compared to 3.0 and 11.0 H, soil moisture content at 1.0 H was consistently higher. This may indicate a shelter effect from the windbreak intercepting radiation and thereby reducing evaporation and transpiration at 1.0 H, relative to distances further from the windbreak. It was often noted during mid-winter that the 1.0 H region was shaded from 12h00 onwards. The windbreak shadow would eventually reach the distance of 3.0 H at 16h00, and then the sun would set over the north-western mountain range at 17h00 to 18h00. This 4 to 6 hour reduction in total daily radiation at 1.0 H was therefore a possible contributing factor to the higher soil moisture levels at this location.

A consistently higher level of soil moisture at 1.0 H compared to any other location indicates that the windbreak did not compete with the adjoining crop for soil moisture. In fact, the higher levels at 1.0 H indicated that the interaction between the windbreak and crop components actually caused an increase in soil moisture at 1.0 H, due to high levels of shading. This conclusion, as well as the absence of surface roots beyond 0.5 H provided further evidence that the young *P. radiata* windbreak did not cause significant below-ground competition at 1.0 H. The shelter effect was more likely to affect the conservation of soil moisture in conditions of high evaporative demand and limited soil moisture than in wetter conditions (Nuberg, 1998; Hough and Cooper, 1988)

2 WOLSELEY SITE 3 (WoS3)

2.1 Method

2.1.1 Wind speed, soil temperature, and soil moisture measurements

The southern *Casuarina cunninghamiana* windbreak at WoS3 was suspected to provide shelter from severe south-easterly winds in spring and summer. At WoS3, the portable weather station operated from 14 September to 9 November 1999 to obtain information concerning microclimate variation in relation to the distance from the southern windbreak. The windbreak had an effective height of 5.0 m. The unit was installed at 3.0 H to the lee (north) of the southern windbreak, from which the following sensors (connected by cables) extended across each research site:

1. The three wind speed sensors (anemometers) were placed at 1.5 m height. From 14 September to 12 October 1999, wind sensors were located at 1.0, 3.0, and 11.0 H on the leeward side from the southern windbreak. From 12 October to 9 November 1999, wind sensors were located at 3.0, 7.0, and 13.0 H. Data were averaged over one hour, from 10-minute intervals.

2. The two soil temperature probes were located at 3.0 and 11.0 H to the leeward side of the southern windbreak, from 14 September to 9 November 1999. Probes were 20 cm below the soil surface. Data were sampled hourly.

3. Nine CS615 water content reflectometer (surface soil moisture content) probes were arranged across the site in a way that allowed for three replications. Therefore, three probes each were located at 1.0, 3.0, and 11.0 H to the leeward side of the southern windbreak. The sample period occurred from 14 September to 9 November 1999. All CS615 measurements were made using the AM416 Relay Multiplexer. Probes were located 20 cm below the soil surface. Data were averaged over one hour, from 10-minute intervals.

The portable weather station also recorded hourly sampled measurements of air temperature, evaporation, relative humidity (RH) and UV light.

Soil samples were collected at specific distances from the southern windbreak on 9 November 1999 to calibrate the data from the soil moisture probes. Samples were collected at 20 cm below the soil surface. Sampled soil was immediately sealed tightly in a labelled tin. Each tin was weighed, and weighed again following oven drying with lids loosened (at 100°C for 24 hours). Tins were then emptied and weighed. Calculations were made using the following formula:

$$\text{MC (\%)} = (\text{undried soil}^{\text{mass}} - \text{dried soil}^{\text{mass}}) / \text{dried soil}^{\text{mass}} \text{ X } 100$$

Data were also included from Department of Water Affairs and Forestry (DWAF) weather station at the "La Plaisante" farm. Data from this weather station included wind speeds, rainfall, temperature, evaporation, and relative humidity for the long term and the current year. Wind speeds from these stations were measured in km / day, so the level of information concerning brief yet severe winds during a day could easily be masked when averaged over the whole day and the whole month. At best, these wind speeds provided information concerning monthly trends.

2.1.2 Regional description

WoS3 was located 6 km south-west of Wolseley (longitude: 19°12′E, latitude: 33°26′S, altitude: 260 m) on the farm "Verrekyker" of Fanie and Elizabeth Redelinghuys. The farm consisted of citrus, pear and peach orchards, and some vineyards. Plate 1.1 in Section $3.2^{\text{Ch. 1}}$ illustrates the location of WoS3 in the Western Cape Region.

Table 1.2.1 shows the summarised long term and 1999 data collected from the "La Plaisante" DWAF weather station located 4 km west of WoS3. The average daily maximum temperature in this region was 30.4°C for the hottest months (January and also February) and the average daily minimum temperature for the coolest month (July) was 6.6°C. The site is in a temperate winter rainfall region, with June having the highest average monthly rainfall (102.1 mm), and January having the lowest average monthly rainfall (11.9 mm). Data for total evaporation and Relative Humidity (RH) are also included in Table 1.2.1.

Table 1.2.1 Long term records and 1999 records of weather data recorded at the "La Plaisante" weather station near Wolseley.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Long term av. wind speed (km / day)	158.6	160.7	145.9	123.4	117.8	125.5	129.0	132.3	137.2	151.5	159.9	158.8
1999 av. wind speed (km / day)	148.2	169.3	130.2	118.3	99.8	104.6	111.9	103.7	127.1	130.4	*	*
1999 av. max. wind speed (km / day)	249.0	269.6	219.0	229.5	210.3	206.0	187.7	226.5	110.1	150.1	*	*
Long term av. daily max. temp. (°C)	30.4	30.4	28.5	24.6	20.6	17.6	17.0	17.6	20.2	23.4	26.5	28.8
Long term av. daily minimum temp. (°C)	15.7	16.0	14.7	12.1	9.3	7.4	6.6	7.0	8.6	10.7	12.8	14.6
1999 av. daily maximum temp. (°C)	32.4	31.2	31.5	26.1	21.1	19.6	18.9	18.8	19.5	25.9	*	*
1999 av. daily minimum temp. (°C)	16.6	17.1	15.7	12.6	10.4	7.4	7.5	7.3	9.7	11.8	*	*
Long term av. total rain (mm)	11.9	16.2	20.8	44.4	81.9	102.1	84.0	83.6	49.3	36.2	24.6	19.0
1999 total rain (mm)	0.7	12.5	0.0	37.8	54.4	104.4	52.1	135.4	115.4	0.2	*	*
Long term av. total evaporation (mm)	301.5	252.6	211.9	131.2	84.7	61.9	65.9	81.7	117.3	184.8	244.5	281.6
1999 total evaporation (mm)	293.7	233.5	214.0	140.0	63.4	52.9	68.2	72.4	99.9	188.2	*	*
Long term av. daily max. RH (%)	86.8	88.1	89.6	91.8	93.0	92.5	93.1	93.2	92.7	90.5	88.2	87.3
1999 av. daily max. RH (%)	90.4	88.1	87.9	88.7	92.4	91.5	89.8	91.2	93.3	88.6	*	*

* Data for November and December 1999 were unavailable.

2.1.3 Site description

An aerial view of WoS3 is shown in Plate 1.2.1, and a profile view of the southern windbreak with adjoining crop strips is shown in Plate 1.3 in Section 3.2 $^{\text{Ch. 1}}$. This site had a *C. cunninghamiana* windbreak with an average effective height (H) of 5.0 m adjoining the north and south borders of a vacant block of land. Distance between the two windbreaks was 94.0 m (18.8 H). The windbreaks were orientated in a northeast-east direction, and gaps were minimal along the windbreak profile. Both of the 2-year old windbreaks were single rowed and the trees were spaced 1.0 m from each other. The width of the experimental site was 20.0 m. The site had remained fallow for the last decade in anticipation of eventual orchard establishment between the two windbreaks in May 2001.

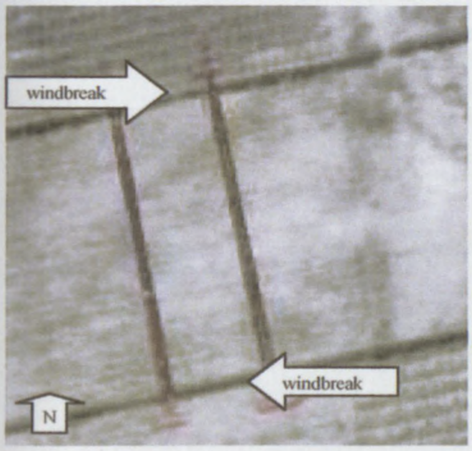

Plate 1.2.1 Aerial view of WoS3. Prevailing winds were south-easterly. Scale 1:2500.

An initial soil investigation on 12 January 1999 provided an insight into the soil variation across the vacant block of land. This investigation involved a rapid collection of surface soil samples spaced at 30.0 m x 30.0 m from each other. The most homogenous 30.0 m x 94.0 m section between both windbreaks was thereby selected for the site.

Soil pits were not excavated at this site as the Dundee 1210 soil classification (Munsell Color Co., 1975) described for another Wolseley site a year earlier was known to be consistent throughout this area (Dr. Freddie Ellis, personal communication). The site description of this earlier Wolseley site (WoS1, located 2 km east of WoS3) is described in Section 4.1.2 $^{\mathrm{Ch.\ 3}}$. On 1 October 1999, three points located across the WoS3 site were drilled with an auger to a depth of 1.2 m to confirm this assumption. The soil profiles from the three soil pits at WoS1 indicated:

1. An orthic A horizon from 0 to 30 cm depth, about 10% clay content, and a fine to medium sand grade.
2. A stratified alluvium material with signs of wetness (C1 and C2 horizon) from 30 to 120 cm depth, about 12% clay content, and a fine to medium sand grade.
3. A stratified alluvium material with signs of wetness (C3 horizon) from 120 to > 140 cm depth, about 3% clay content, and a medium to coarse sand grade.

Munsell colour codes for surface soils at 1.0, 3.0, and 11.0 H were also described.

2.1.4 Experimental design

The general shape of the design was a 25.0 m wide vacant block extending 94.0 m between the two windbreaks. Access tracks were not present along the windbreaks, and therefore the experimental design extended directly to each of the windbreaks. Each windbreak extended for approximately 500 m on either side of the site. Other crops and orchards existed on the other side of each of the windbreaks, thus preventing any measurements beyond the site boundary.

2.1.5 Windbreak porosity

Windbreak porosity was estimated using two photographs of 3.0 m x 3.0 m samples for each windbreak. Each image was scanned and then posturised by computer. The porosity was calculated using an image digitalisation programme that calculated the number of darker pixels compared to lighter pixels. The porosity of the two images from each windbreak was then averaged.

2.2 Results

2.2.1 WoS3 wind speed

All following distances described for this sampling period at WoS3 were located to the lee of the southern windbreak. Table 1.2.2 in Section 2.2.1.1 $^{\text{Ch. 2}}$ summarises the variation of wind speeds at 11.0, 3.0, and 1.0 H from southern WoS3 windbreak. Table 1.2.3 in Section 2.2.1.2 $^{\text{Ch. 2}}$ summarises the variation of wind speeds at 13.0, 7.0, and 3.0 H from the southern WoS3 windbreak.

Wind speed data were based on the averaged value during each hour, from samples taken at 10-minute intervals. Wind speed units were represented as m / s (1.0 m / s = 3.6 km / hr). The wind speed for each hour was the averaged value taken from six sampled wind speeds taken at 10-minute intervals. Due to this averaging over each hour, the magnitude of the wind speeds tended to be somewhat subdued compared to some of the momentary gusts of wind. From the highly publicised gale force winds that occurred throughout the Western Cape Region from 16 October to 20 October 1999, exposed wind speeds recorded by the portable weather station at WoS3 ranged from 4.0 to 6.0 m / s. The averaged hourly wind speed of 4.0 m / s was therefore considered to be the minimum value of gale force winds.

2.2.1.1 Sample period from 14 September to 12 October 1999

Table 1.2.2 Summary of the variation of average hourly wind speed* at 11.0, 3.0, and 1.0 H to the lee of the southern WoS3** windbreak.

wind speed (m/s) range (v)	hours	frequency (%)	wind speed (m/s) at 11 H	wind speed (m/s) at 3 H	wind speed (m/s) at 1 H	wind speed reduction (m/s) at 3 H compared to 11 H	wind speed reduction (m/s) at 1 H compared to 11 H	wind speed reduction (%) at 3 H compared to 11 H	wind speed reduction (%) at 1 H compared to 11 H
6.0 < v < 7.0	1	0.2	6.24	2.45	4.21	3.79	2.03	60.71	32.53
5.0 < v < 6.0	1	0.2	5.57	2.48	4.19	3.09	1.39	55.43	24.88
4.0 < v < 5.0	10	1.5	4.45	2.15	3.11	2.30	1.34	51.59	30.15
3.0 < v < 4.0	45	6.8	3.26	2.12	2.29	1.14	0.98	35.04	29.93
2.0 < v < 3.0	152	22.8	2.43	1.63	1.68	0.80	0.75	32.94	30.92
1.0 < v < 2.0	225	33.8	1.48	0.76	0.72	0.72	0.75	48.63	50.93
0.0< v < 1.0	232	34.8	0.52	0.18	0.12	0.35	0.41	66.59	77.66
total	666	100.0	1.54	0.87	0.88	0.67	0.66	43.41	42.74
north winds	480	72.0	1.46	0.55	0.64	0.91	0.82	62.55	56.08

* Wind speed was recorded hourly. Each hourly unit was averaged from sample measurements every 10 minutes. Sampling period occurred from 14 September to 12 October 1999.

** Effective tree height (H) was 5.0 m. All wind speed sensors were located on the leeward side of the windbreak.

The highest wind speed recorded was 6.24 m / s, which occurred at 18h00, on 6 October 1999. Figure 1.2.1 shows the variation of all recorded wind speeds at 11.0, 3.0, and 1.0 H from the southern WoS3 windbreak. Figure 1.2.2 shows the relationship of all recorded wind speeds at 3.0 and 1.0 H from the southern WoS3 windbreak, according to corresponding sorted 11.0 H wind speeds. Figure 1.2.3 shows the correlation of all recorded wind speeds at 11.0 H with that at 3.0 and 1.0 H from the southern WoS3 windbreak. Figure 1.2.4 shows the correlation of wind speeds from the southerly direction only at 11.0 H with that at 3.0 and 1.0 H from the southern WoS3 windbreak.

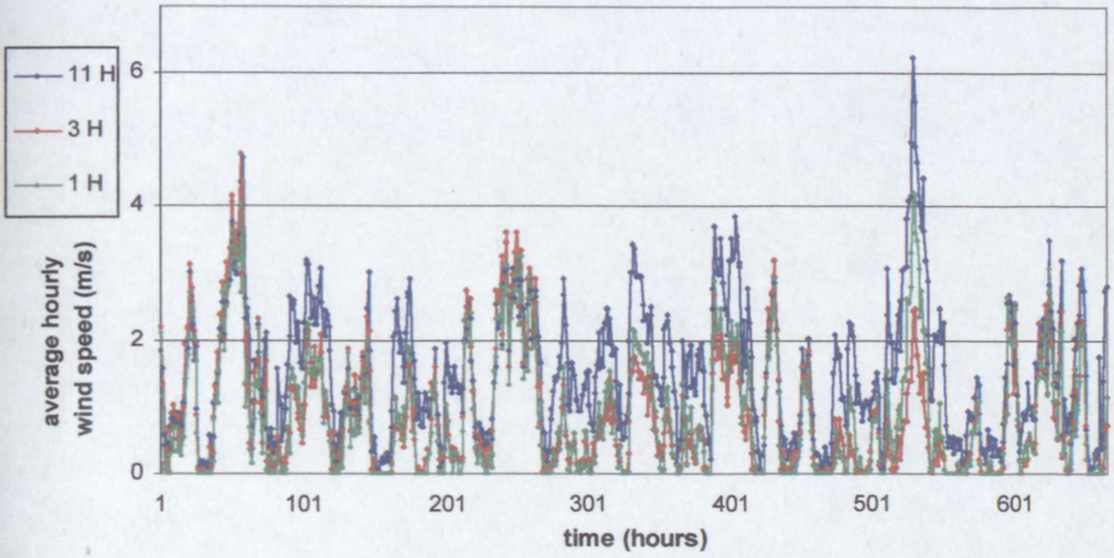

Figure 1.2.1 Variation of all recorded wind speeds at 11.0, 3.0, and 1.0 H from the southern *C. cunninghamiana* windbreak at WoS3. Effective tree height (H) was 5.0 m. Data points have been joined to enhance visual presentation.

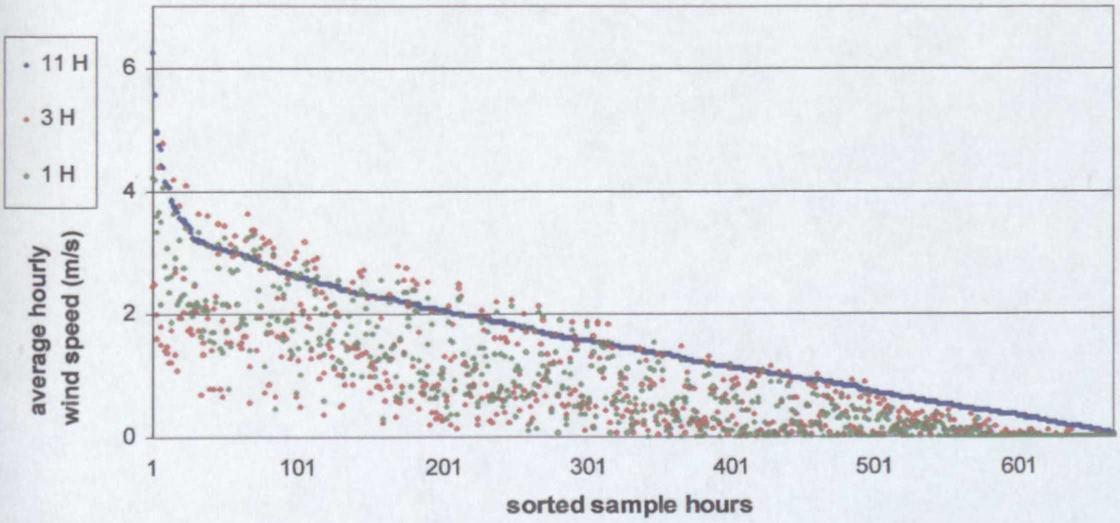

Figure 1.2.2 Relationship of all recorded wind speeds at 3.0 and 1.0 H from the southern *C. cunninghamiana* windbreak at WoS3, according to corresponding sorted 11.0 H wind speeds. Effective tree height (H) was 5.0 m.

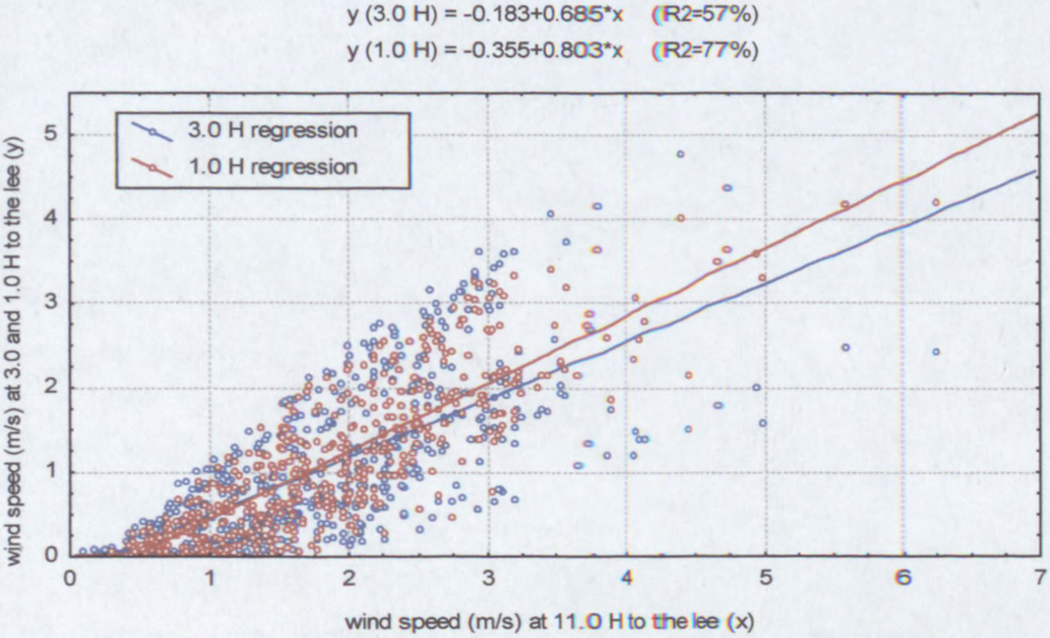

Figure 1.2.3 Correlation of all recorded wind speeds at 11.0 H with that at 3.0 and 1.0 H from the southern *C. cunninghamiana* windbreak at WoS3. Effective tree height (H) was 5.0 m.

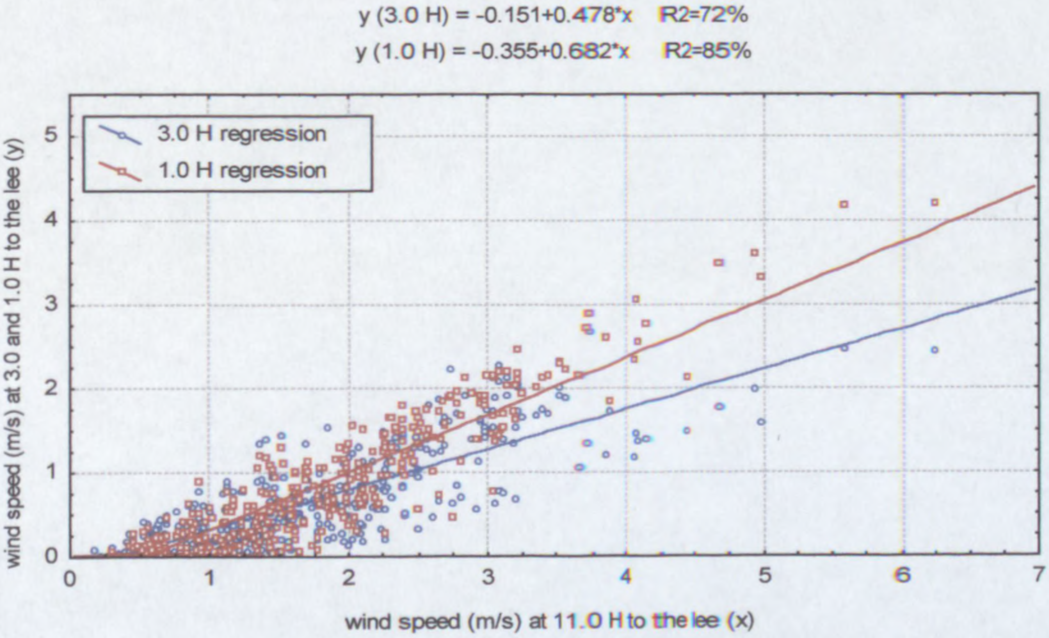

Figure 1.2.4 Correlation of wind speeds (from the southerly direction only) at 11.0 H with that at 3.0 and 1.0 H from the southern *C. cunninghamiana* windbreak at WoS3. Effective tree height (H) was 5.0 m.

2.2.1.2 Sample period from 12 October to 9 November 1999

Table 1.2.3 Summary of the variation of average hourly wind speed* at 13.0, 7.0, and 3.0 H to the lee of the southern WoS3** windbreak.

wind speed (m/s) range (v)	hours	frequency (%)	wind speed (m/s) at 13 H	wind speed (m/s) at 7 H	wind speed (m/s) at 3 H	wind speed reduction (m/s) at 7 H compared to 13 H	wind speed reduction (m/s) at 3 H compared to 13 H	wind speed reduction (%) at 7 H compared to 13 H	wind speed reduction (%) at 3 H compared to 13 H
6.0 < v < 7.0	8	1.2	6.38	4.91	2.60	1.46	3.77	22.96	59.20
5.0 < v < 6.0	37	5.5	5.48	4.07	2.08	1.41	3.40	25.70	61.99
4.0 < v < 5.0	67	9.9	4.40	3.23	1.57	1.17	2.83	26.58	64.36
3.0 < v < 4.0	116	17.2	3.44	2.42	1.03	1.02	2.41	29.59	70.15
2.0 < v < 3.0	137	20.3	2.50	1.64	0.53	0.86	1.97	34.26	78.92
1.0 < v < 2.0	158	23.4	1.56	1.30	0.70	0.26	0.86	16.41	55.22
0.0 < v < 1.0	151	22.4	0.43	0.33	0.21	0.10	0.23	23.44	52.40
total	674	100.0	2.37	1.73	0.79	0.64	1.58	27.05	66.56
S.E. winds	481	71.4	2.87	1.93	0.77	0.93	2.09	32.58	73.03

* Wind speed was recorded hourly. Each hourly unit was averaged from sample measurements each 10 minutes. Sampling period occurred from 12 October to 9 November 1999

** Effective tree height (H) was 5.0 m. All wind speed sensors were located on the leeward side of the windbreak.

For the sampling period from 14 September to 9 November 1999, the highest wind speed recorded was 6.6 m / s at 18h00 on 18 October 1999. Severe south easterly winds dominated this sample period. Continuous gale force south-easterly winds occurred from 16 October 1999 to 20 October 1999.

Figure 1.2.5 shows the variation of wind speeds at 13.0, 7.0, and 3.0 H from the southern WoS3 windbreak, in relation with time. Figure 1.2.6 shows the relationship of wind speed at 7.0 and 3.0 H from the southern WoS3 windbreak, according to corresponding sorted 13.0 H wind speeds. Figure 1.2.7 shows the correlation of all recorded wind speeds at 13.0 H with that at 7.0 and 3.0 H from the southern WoS3 windbreak. Figure 1.2.8 shows the correlation of wind speeds (from the southerly direction only) at 13.0 H with that at 7.0 and 3.0 H from the southern WoS3 windbreak.

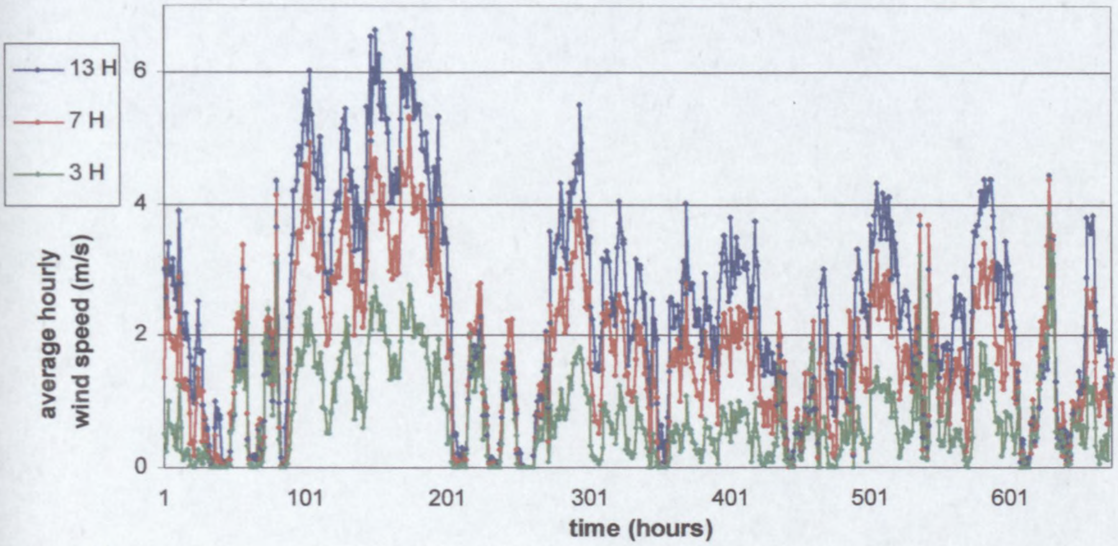

Figure 1.2.5 Variation of wind speeds at 13.0, 7.0, and 3.0 H from the southern *C. cunninghamiana* windbreak at WoS3. Effective tree height (H) was 5.0 m. Data points have been joined to enhance visual presentation.

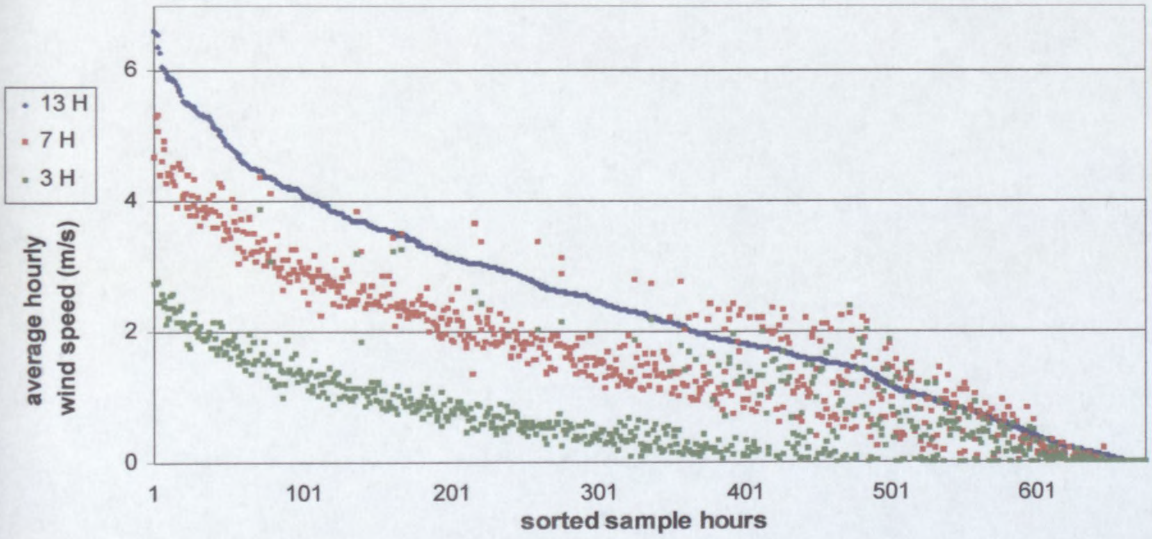

Figure 1.2.6 Relationship of wind speed at 7.0 and 3.0 H from the southern *C. cunninghamiana* windbreak at WoS3, according to corresponding sorted 13.0 H wind speeds. Effective tree height (H) was 5.0 m.

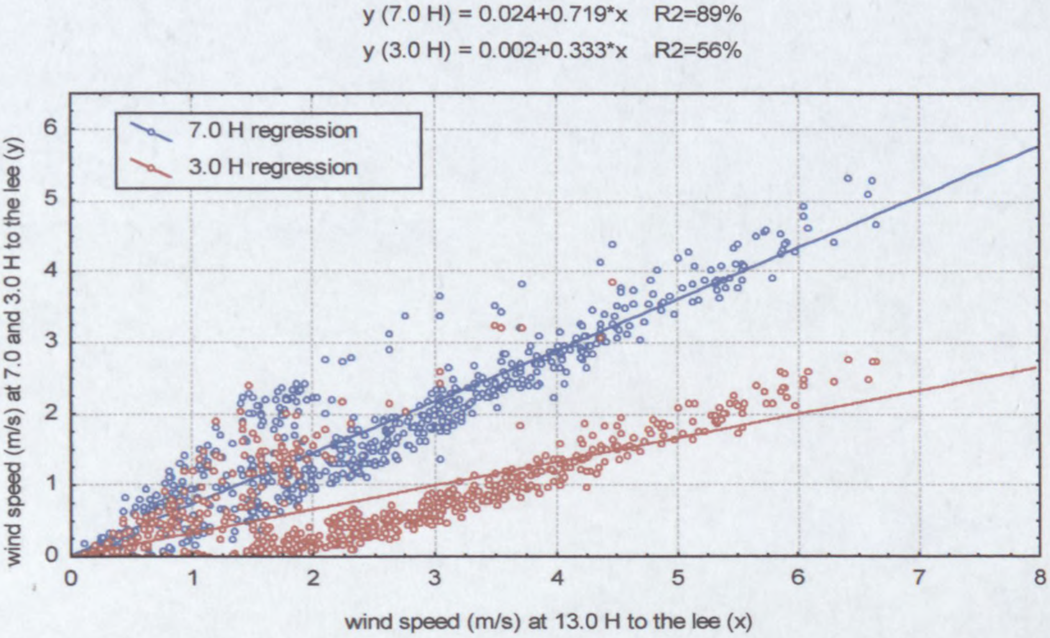

Figure 1.2.7 Correlation of all recorded wind speeds at 13.0 H with that at 7.0 and 3.0 H from the southern *C. cunninghamiana* windbreak at WoS3. Effective tree height (H) was 5.0 m.

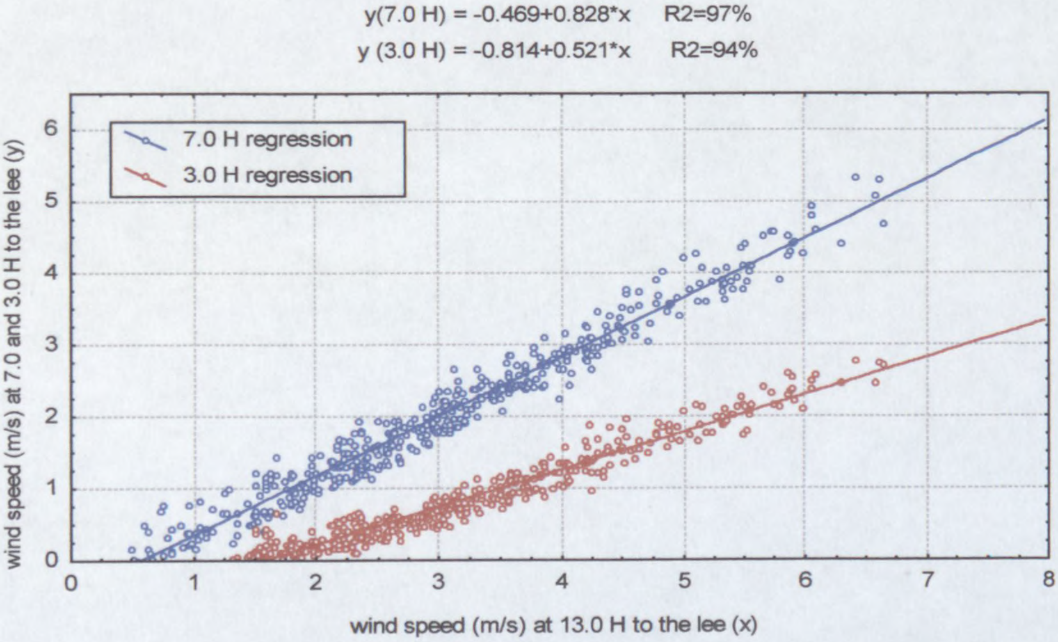

Figure 1.2.8 Correlation of wind speeds (from the southerly direction only) at 13.0 H with that at 7.0 and 3.0 H from the southern *C. cunninghamiana* windbreak at WoS3. Effective tree height (H) was 5.0 m.

2.2.2 WoS3 soil temperature

Soil temperature was sampled once every hour. Figure 1.2.9 shows the variation of soil temperature at 3.0 and 11.0 H to the lee of the southern WoS3 windbreak. Corresponding wind speeds at 11.0 H to the lee are also shown. Figure 1.2.10 shows the difference in soil temperature between 3.0 and 11.0 H to the lee of the southern WoS3 windbreak. Corresponding wind speeds at 11.0 H to the lee are also shown. A positive temperature indicates a higher temperature at 3.0 H, compared to that at 11.0 H.

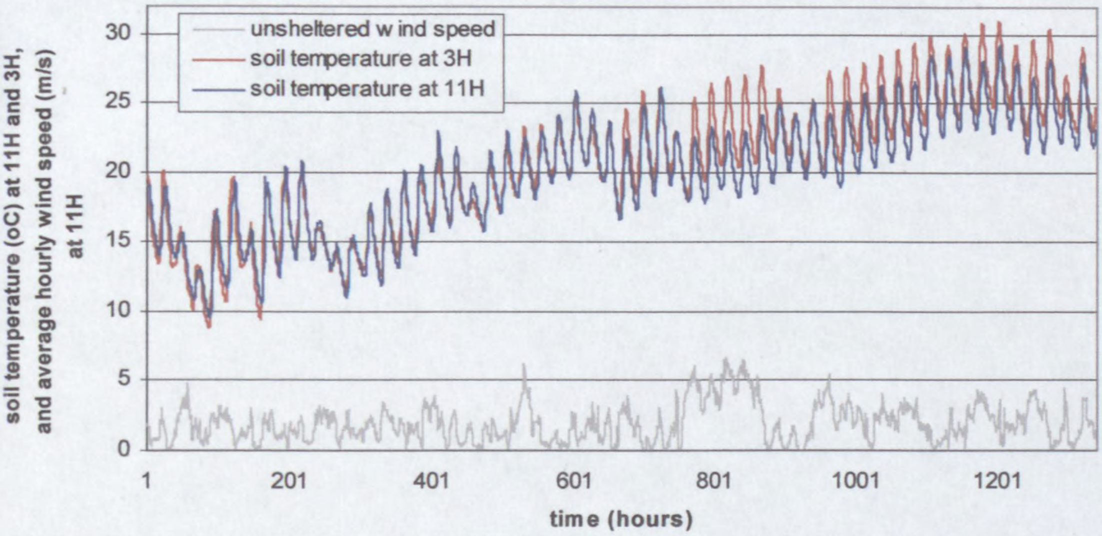

Figure 1.2.9 Variation of soil temperature at 3.0 and 11.0 H to the lee of the southern *C. cunninghamiana* windbreak at WoS3. Corresponding wind speeds at 11.0 H to the lee are also shown. Effective tree height (H) was 5.0 m. Data points have been joined to enhance visual presentation.

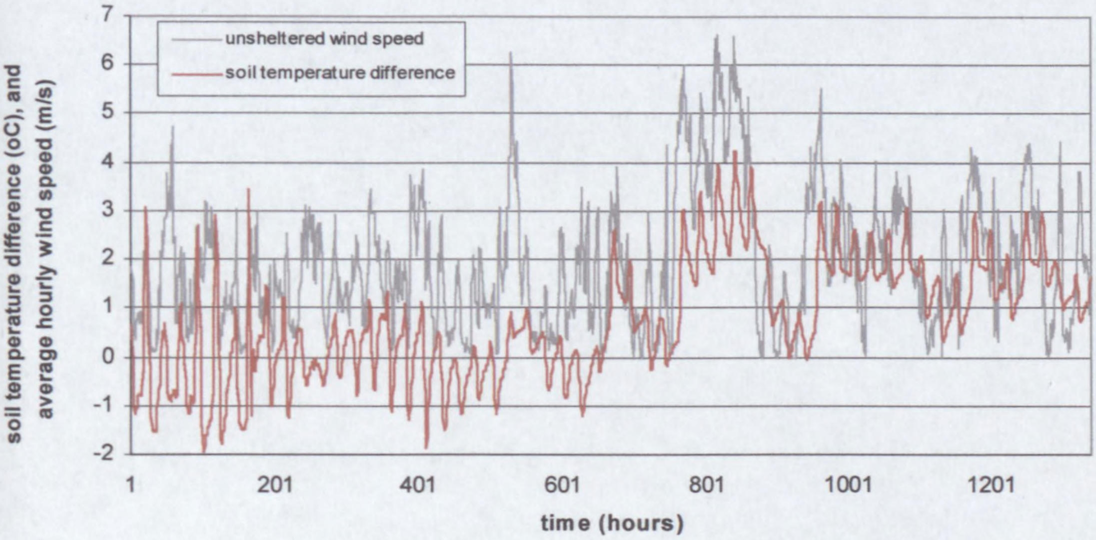

Figure 1.2.10 Difference in soil temperature between 3.0 and 11.0 H to the lee of the southern *C. cunninghamiana* windbreak at WoS3. Corresponding wind speeds at 11.0 H to the lee are also shown. A positive temperature indicates a higher temperature at 3.0 H, compared to that at 11.0 H. Effective tree height (H) was 5.0 m. Data points have been joined to enhance visual presentation.

2.2.3 WoS3 soil moisture

Soil moisture data were based on the average value during each hour from samples taken at 10-minute intervals. Figure 1.2.11 shows the averaged variation of soil moisture content at 11.0, 3.0, and 1.0 H to the lee of the southern WoS3 windbreak. Figure 1.2.12 shows the averaged variation of soil moisture content at 11.0, 3.0, and 1.0 H to the lee of the southern WoS3 windbreak, from a sample period of 200 hours. Corresponding wind speeds at 11.0 H to the lee are also shown. Data from 3.0 and 1.0 H were each averaged from 3 soil probes. At 11.0 H, 2 soil probes failed to function so data at this distance were represented by 1 soil probe only. For 11.0 and 1.0 H, the sudden drop in soil moisture content at approximately 400 hours was caused by adjustments of soil probes during site maintenance procedures.

A consistent dark greyish brown 10YR42 wet Munsell colour code (Munsell Color Co., 1975) was described for the soils at 1.0 and 3.0 H. At 11.0 H, the soil description changed slightly to a brown 10YR43 wet Munsell colour code.

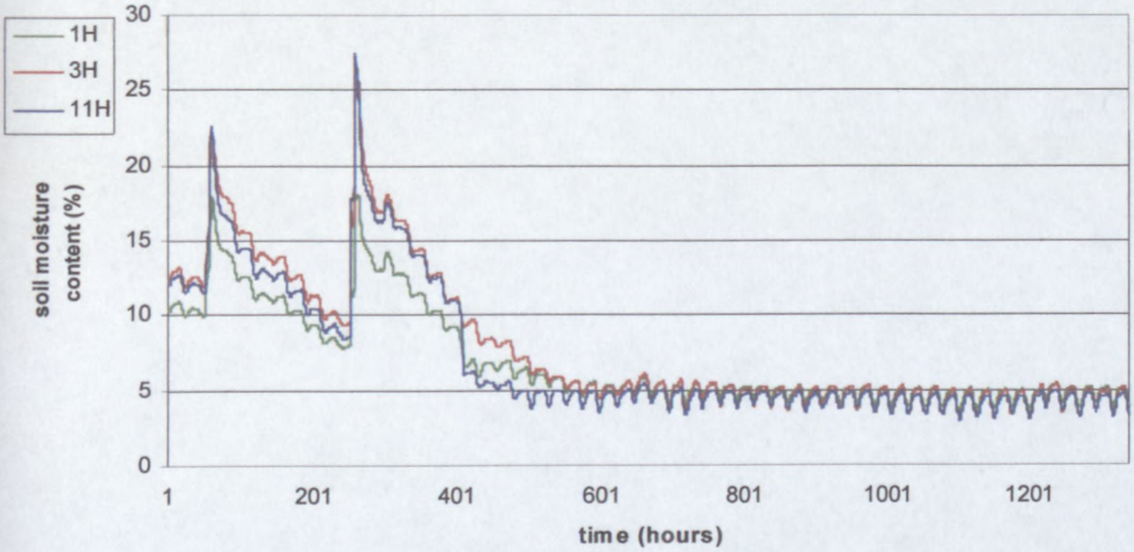

Figure 1.2.11 Averaged variation of soil moisture content at 11.0, 3.0, and 1.0 H to the lee of the southern *C. cunninghamiana* windbreak at WoS3*. Effective tree height (H) was 5.0 m. For 11.0 and 1.0 H, the sudden drop in soil moisture content at approximately 400 hours was caused by

adjustments of soil probes during site maintenance procedures. Data points have been joined to enhance visual presentation.

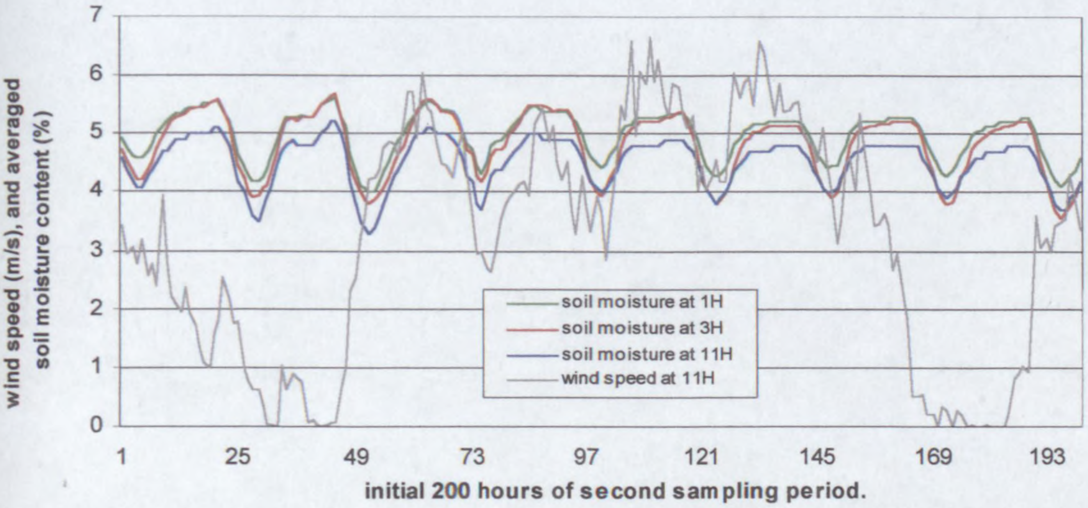

Figure 1.2.12 Averaged variation of soil moisture content at 11.0, 3.0, and 1.0 H to the lee of the southern *C. cunninghamiana* windbreak at WoS3, from a sample period of 200 hours*. Corresponding wind speeds at 11.0 H to the lee are also shown. Effective tree height (H) was 5.0 m. Data points have been joined to enhance visual presentation.

* Data from 3.0 and 1.0 H were each averaged from three soil probes. At 11.0 H, two soil probes failed to function so data at this distance were represented by one soil probe only.

2.3 Discussion

2.3.1 WoS3 Wind speed

2.3.1.1 Sample period from 14 September and 12 October 1999

All following distances described for this sampling period at WoS3 were located to the lee of the southern windbreak. During this first sampling period at WoS3, wind sensors were located at 1.0, 3.0, and 11.0 H (Table 1.2.2 and Figure 1.2.1 in Section 2.2.1.1 $^{\text{Ch. 2}}$). Despite the lack of strong southerly winds and the frequent occurrence of interfering northerly and north-westerly winds, wind speeds at 11.0 H tended to be higher than the wind speeds at 1.0 and 3.0 H. The general shelter effect is further illustrated in Figure 1.1.10, which illustrates the relationship of leeward wind speeds at 3.0 and 1.0 H according to corresponding sorted wind speeds at 11.0 H. The DWAF Wolseley weather station also recorded that average monthly wind speeds throughout the year were below average, especially from May to October 1999.

The average wind speed at 11.0 H was 1.5 m / s, compared to 0.8 and 0.9 m / s at 3.0 and 1.0 H respectively. In relation to 11.0 H, the level of wind speed reduction at both 3.0 and 1.0 H was 43%. Southerly winds occurred for 72% of the sampling period, indicating that these winds were prevalent but the magnitude was probably too low to cause damage to crops. The similarly low wind speeds at 1.0 and 3.0 H indicated that the maximum level of shelter extended to at least 3.0 H.

When the northerly winds were excluded, the average wind speed at both 3.0 and 1.0 H was 0.6 m / s, compared to 1.5 m / s at 11.0 H. The exclusion of northerly winds increased the wind speed reduction level from 43 to 63% at 3.0 H and from 42 to 56% at 1.0 H. This indicated that the northerly winds reduced the effectiveness of the general shelter effect by 20 and 14% at 3.0 and 1.0 H respectively. Such a significant reduction in the shelter effect may necessitate the requirement of a series of parallel windbreaks at WoS3 to provide maximum shelter from both winds and south-westerly winds during this period of the year.

Figure 1.2.3 illustrates a poor correlation between wind speeds at 11.0 H and those at 3.0 ($r^2 = 57\%$). A better correlation occurred between wind speeds at 11.0 H and those at 1.0 H ($r^2 = 77\%$). To improve the correlation of the shelter effect, the northerly winds (contaminating data comprising 28% of the total data) were excluded in Figure 1.2.4 to produce improved regressions between wind speeds at 11.0 H and those at 3.0 ($r^2 = 72\%$) and 1.0 H ($r^2 = 85\%$). However, these improved correlations were relatively poor compared to the correlations observed for each sampling period at ViS1, discussed in Section 1.3.1 $^{\text{Ch. 2}}$. The regression equations at WoS3 were linear:

For 3.0 H, $y = -0.151 + 0.478x$,

For 1.0 H, $y = -0.355 + 0.682x$,

where x = wind speed at 11.0 H to the lee, and
y = wind speed at 3.0 or 1.0 H to the lee (if $y < 0$, then $y = 0$)

As wind speed for each hour was the averaged value taken from six sampled wind speeds taken at 10-minute intervals, the magnitude of the recorded wind speeds were subdued compared to some of the momentary gusts of wind. From the gale force winds that occurred throughout the Western Cape Region from 16 October to 20 October 1999 during the following sampling period at WoS3 (described in Section 2.3.1.2$^{\mathrm{Ch.\ 2}}$), exposed wind speeds recorded by the portable weather station ranged from 4.0 to 6.0 m / s. The averaged hourly wind speed of 5.0 m / s was therefore considered to be gale force

According to this improved regression equation, gale force winds of 5.0 m / s at 11.0 H would be reduced to 2.8 and 3.1 m / s at 3.0 and 1.0 H respectively. Therefore, for a southerly wind for which the WoS3 windbreak was designed, a 5.0 m/s wind speed reduction was predicted to be 64 and 39% at 3.0 to 1.0 H respectively, for this particular sampling period. Caution is necessary concerning these predictions due to the poor correlation of the regressions at 1.0 to 3.0 H. The similarly low wind speeds at 1.0 and 3.0 H to the lee indicated that the maximum level of shelter extended to 3.0 or 4.0 H to the lee.

Other investigations similarly reported that maximum wind speed reductions occurred in the zone ranging from 3.0 to 6.0 H (Cleugh and Hughes, 2000; Cleugh, 1998; Sun and Dickinson, 1997; Hodges and Brandle, 1996; Bird, 1988, Ujah and Adeoye, 1984). The area of maximum shelter was estimated by Nuberg (1998) to range from 4.0 and 12.0 H. From wind tunnel tests, Tibke (1988) reported that maximum shelter extended to 9.0 H.

The lower wind speed reductions at 1.0 H indicated increased turbulence at this location, compared to 3.0 H (Table 1.2.2 of Section 2.2.2.1 $^{\text{Ch. 2}}$). Notably, when exposed wind speeds increased beyond 4.0 m / s, the wind speeds at 1.0 H tended to become higher than the wind speeds at 3.0 H. At exposed wind speeds below 4.0 m / s, respective wind speeds at 1.0 and 3.0 H were almost identical. This suggested that turbulence immediately behind the windbreak might have been responsible for the slightly reduced shelter effect at 1.0 H, compared to 3.0 H at higher exposed wind speeds. Increased jetting of air through the windbreak at higher wind speeds may also have added to this localised turbulence. Maximum shelter rarely occurred directly next to the windbreak, suggesting that this was due to the jetting of the wind as it immediately passed through the trees (Nuberg, 1998). Field experiments in Germany over six years indicated that the shelter effect did not occur until 1.8 H to the leeward side of the windbreak (Pretzechel *et al.*, 1991).

From Figure 1.2.1, the sharp rise in wind speeds at approximately 520 hours was attributed to the first south-easterly wind for the season. Note the increased divergence of the wind speeds between the exposed and sheltered zones at this time, resulting from an increased shelter effect for this particular wind direction. However, this brief occurrence of the anticipated severe south-easterly winds was insufficient to have an impact on the regression lines shown in Figure 1.2.3 and 1.2.4.

A windward shelter effect was also evident. The reduction of the effectiveness of the shelter effect due to northerly winds at 1.0 H was 6% less than that at 3.0 H. The improved regression equations in Figure 1.2.4 also had less impact on the r^2 value for the 1.0 H data, compared to the 3.0 H data. This was attributed to reduced fluctuations of northerly wind speeds at 1.0 H, compared to 3.0 H. Effective windbreaks provide shelter for up to 5.0 H on the windward side (Cleugh and Hughes, 2000; Haigh, 1994), although a smaller windward range of 1.0 to 3.0 H has also been suggested (Hodges and Brandle, 1996; Pretzechel *et al.*, 1991; Pienaar, 1987).

2.3.1.2 Sample period from 12 October and 9 November 1999

All following distances described for this sampling period at WoS3 were located to the lee of the southern windbreak. During the second sampling period at WoS3, wind sensors were located at 3.0, 7.0, and 13.0 H. The resultant data are summarised in Table 1.2.3 and illustrated in Figure 1.2.5 (Section 2.2.1.2$^{\text{Ch. 2}}$). Severe south-easterly winds dominated this period, resulting in a highly improved overall shelter effect, compared to the previous sampling period. Southerly winds occurred for 71% of the sampling period, indicating that these winds were prevalent and certainly damaging to crops. The emergence of the prevailing south-easterly winds resulted in average hourly wind speeds in the exposed 13.0 H zone to increase to 2.4 m / s, compared to 1.5 m / s at 11.0 H for the previous sampling period.

Notably, the average hourly wind speed at 3.0 H dropped from 0.9 m / s in the previous sampling period to 0.8 m / s, despite the sharp increase in exposed wind speeds. This resulted in a wind speed reduction of 67% at 3.0 H, relative to the exposed wind speeds at 13.0 H. This pronounced shelter effect was most likely due to an improved general ability for the windbreak to intersect south-easterly winds, which the windbreak was intentionally designed to face. The dominance of the south-easterly winds in this sampling period allowed the well-orientated windbreak to approach its maximum sheltering potential.

The average wind speed at 7.0 H was 1.7 m / s, which translated to a 27% reduction in wind speed relative to the exposed wind speed at 13.0 H. The wind speeds at 7.0 H indicated that this distance was within an intermediate zone between the sheltered zone at 3.0 H and the exposed zone at 13.0 H.

The consistent shelter effect at specific distances from the windbreak is illustrated in Figure 1.2.5, where the wind speeds at each distance are highly distinct from each other and highly ordered for almost the entire sampling period. The distinct shelter effect at each distance is further illustrated in Figure 1.2.6, which illustrates the relationship of leeward wind speeds at 7.0 and 3.0 H according to corresponding sorted wind speeds at 13.0 H. Figure 1.2.6 also illustrates the interference in the distinct trends when 13.0 H wind speeds were below 2 m / s. This was due to mild northerly winds that the windbreak was not designed to intercept.

When the northerly winds were excluded, the average wind speed at 7.0 and 3.0 H was 1.9 and 0.8 m / s respectively, compared to 2.8 m / s at 13.0 H. The exclusion of northerly winds increased the wind speed reduction level from 27 to 32% at 7.0 H and from 67 to 73% at 3.0 H. Therefore, the northerly winds reduced the effectiveness of the general shelter effect by 5 and 6% at 7.0 and 3.0 H respectively. Figure 1.2.7 illustrates a high correlation between wind speeds at 13.0 H and those at 7.0 H ($r^2 = 89\%$). A poor correlation occurred between wind speeds at 13.0 H and those at 3.0 H ($r^2 = 56\%$).

To improve the correlation of the shelter effect, the northerly winds (contaminating data comprising 29% of the total data) were excluded. For data that recorded no wind speed (0.00 m/s) at 7.0 H, data below 0.05 m/s at 13.0 H were excluded. For data that recorded no wind speed (0.00 m/s) at 3.0 H, data below 1.32 m/s at 13.0 H were excluded. The data excluded actually enhanced the general shelter effect, but were excluded to allow an improved fit of the linear regression equations in regards to the general trend. Figure 1.2.8 shows the improved correlations between wind speeds at 13.0 H and those at 3.0 ($r^2 = 97\%$) and 7.0 H ($r^2 = 94\%$). These correlations were a notable improvement compared to the previous sampling period at WoS3, described in Section 2.3.1.1 $^{\text{Ch. 2}}$. The regression equations were linear:

For 7.0 H, $y = -0.469 + 0.828x$,

For 3.0 H, $y = -0.814 + 0.521x$,

where x = wind speed at 13.0 H to the lee, and
y = wind speed at 7.0 or 3.0 H to the lee (if $y < 0$, then $y = 0$)

As wind speed for each hour was the averaged value taken from six sampled wind speeds taken at 10-minute intervals, the magnitude of the recorded wind speeds were subdued compared to some of the momentary gusts of wind. From the gale force winds that occurred throughout the Western Cape Region from 16 October to 20 October 1999, exposed wind speeds recorded by the portable weather station at WoS3 ranged from 4.0 to 6.0 m / s. The averaged hourly wind speed of 5 m / s was therefore considered to be gale force

According to this improved regression equation, gale force winds of 5.0 m / s at 13.0 H would be reduced to 3.6 and 1.8 m / s at 7.0 and 3.0 H. Therefore, for a southerly wind for which the WoS3 windbreak was designed, a 5.0 m/s wind speed reduction was predicted to be 28 and 64% at 7.0 to 3.0 H respectively, for this particular sampling period. The extent of the leeward shelter effect was indicated by the intermediate wind speeds recorded at 7.0 H. If wind speed reductions dropped from 73% at 3.0 H to 33% at 7.0 H, then it would be reasonable to suggest that the shelter effect decreased to a negligible level at 9.0 or 10.0 H.

Other investigations also concluded that intermediate shelter extended to approximately 10.0 H (Cleugh, 1998; Hodges and Brandle; 1996, Pretzechel *et al.*, 1991; and Dickey, 1988). There are other estimates of the intermediate shelter effect extending to 12.0 H (Bird, 1988), 16 H (Banzhaf *et al.*, 1992; Ujah and Adeoye; 1984). There are also estimates of shelter extending as far as 20.0 H (Haigh, 1994; Sun and Dickinson, 1994; Rocheleau *et al.*, 1988) and 30.0 H (Cleugh and Hughes, 2000; Marshall, 1967).

Basing studies in Western Australia on *P. radiata* windbreaks and adjoining wheat crops, Bird (1988) noted that wind speeds were reduced by 50 to 80% at 12.0 H, compared to unsheltered wind speeds. Windbreaks at intervals of 12.5 H reduced wind speeds by 50%, and at intervals of 25.0 H resulted in a 33% reduction (Bird *et al.*, 1992).

The smaller extent of shelter at WoS3 (and ViS1) was attributed to the severe winds. On fruit farms in the Western Cape Region, windbreaks were spaced at a distance of 12.0 to 14.0 H (although 10.0H has been recommended) with the objective of decreasing the average wind speed throughout the orchard by at least 30% (Myburgh and Viljoen, 1979). From the results at WoS3, such a consistently high level of shelter cannot be considered to be possible for severe wind speeds. A recent trend for closer spacing of windbreak networks throughout the orchard regions of the Western Cape Region may be an indication of a growing level of caution by farmers for prevailing winds. It may also be an indication of a growing level of respect by farmers for the benefits of windbreaks on their crops.

2.3.2 WoS3 soil temperature

At WoS3, soil temperature probes were located at 3.0 and 11.0 H to the lee from 14 September to 9 November 1999 (Figures 1.2.9 and 1.2.10 in Section 2.2.3 $^{\text{Ch. 2}}$). Readings were recorded once every hour. There was little sustained soil temperature difference between the two locations until the first south-easterly wind occurred at approximately 550 hours. From this time, strong to gale force south-easterly winds on a sustained level resulted in higher leeward soil temperatures at 3.0 H than at 11.0 H. Soil temperatures at 3.0 H to the lee were up to 4°C higher relative to the soil temperatures at 11.0 H.

The high level of correlation between soil temperature and exposed wind speed is best illustrated in Figure 1.2.10. High (but briefly occurring) wind speeds had little effect on the soil temperature differences. It was the strong and sustained wind speeds that caused the increased leeward soil temperatures at 3.0 H, compared to 11.0 H. Subsequently the five days of consistent gale force winds produced the greatest temperature differences. A reduction of heat flux due to a reduced level of turbulent transfer in the sheltered zone resulted in higher temperatures, relative to the unsheltered zone (Cleugh, 1998; Nuberg, 1998).

From a series of wind tunnel measurements, Cleugh and Hughes (2000) noted that the maximum increase in air temperature and humidity occurred at the location of minimum wind speed. Air temperature and humidity levels increased with reduced porosity (and hence with increased windbreak shelter). The maximum increase in air temperatures near the surface was 0.14, 0.73, and 1.42°C for the low, medium, and high porosity windbreaks respectively. In the savannah zone of Sudan, Ujah and Adeoye (1984) also reported that maximum air temperatures were 0.8 to 1.5°C higher in the sheltered zone than in the unsheltered zone.

This increase in soil temperature due to reduced wind speeds potentially has significant implications on the growth and production of crops. The temperature component of the shelter effect may be critical at specific stages in the development of crops. Increased temperatures found in sheltered conditions favour vegetative growth over reproductive growth (Nuberg, 1998; Hodges and Brandle, 1996). Increased growth of sheltered cotton occurred only when temperatures were lower than usual (Barker *et al.*, 1985). The increase in temperature under shelter possibly allowed plants to be closer to their optimum temperature for growth. This may explain why winter cereals have been known to respond better to shelter than spring cereals.

Tree windbreaks contribute to more rapid growth during spring and autumn when air temperatures are cooler. In Nebraska, the warmer soil in fields protected by tree windbreaks reduced the level of frost injury to autumn vegetables compared to exposed areas (Hodges and Brandle, 1996). From a *Casuarina glauca* windbreak in northern Tunisia, Benzarti (1999) reported that in wetter conditions the significant increases in plant yield were attributed to increased temperatures from a shelter effect. These temperature increases were close to the thermal optimum level for the growth of the adjoining lucerne (*Medicago sativa*) crop. C4 plants (such as sorghum, soybean, cotton and maize) exhibit higher maximum thermal thresholds, hence are likely to be more responsive to increased temperatures from a shelter effect than for C3 plants (such as lucerne and tomato) (Doorenboos and Kassaam, 1980). In cool and wet conditions in

Tunisia, Benzarti (1989) attributed a 100% increase in the yield of well-watered and sheltered berseem (*Trifolium alexandrinum,* a leguminous plant related to lucerne) to increased temperatures.

However, during drought conditions in hotter climates, Jensen (1993) concluded that windbreaks were detrimental to crops because they increased daytime temperatures beyond the optimum levels. During hot and dry conditions, a sheltered lucerne crop showed greater levels of stress than the respective crop in the exposed zone (Benzarti, 1999). Under these circumstances, the windbreak effect on production and water-use efficiency was negative. Increased temperatures affected both evapo-transpiration and biomass production so that water-use efficiency remained unmodified.

The leeward extent of microclimate changes is much smaller than the leeward extent of wind speed reduction (Cleugh and Hughes, 2000). This implies that direct mechanical impacts of wind on crops will occur over a much larger extent than indirect effects such as temperature and humidity changes.

2.3.3 WoS3 soil moisture

Soil probes located at 1.0, 3.0, and 11.0 H from the southern WoS3 windbreak did not indicate that soil moisture was influenced by the shelter effect from 14 September to 9 November 1999 (Figure 1.2.10 in Section 2.2.3 $^{\text{Ch. 2}}$). Soil moisture data were based on the averaged value during each hour, from samples taken at 10-minute intervals.

Figure 1.2.11 illustrates the variation of wind speed at 11.0 H and the variation of soil moisture content at 1.0, 3.0, and 11.0 H, in relation to the initial 200 hours of the second sampling period. Severe south-easterly winds dominated this part of the second sampling period, so any influence of the windbreak on soil moisture content would have been most visible during this time. However, the soil moisture variation at each location did not indicate a soil-moisture conservation effect caused by the windbreak, regardless of wind speed.

There was some variation of soil moisture content between each location, but this was most likely due to subtle soil variations rather than any shelter effect. Even the slightest variations in sand content have the potential to affect soil moisture levels, and thereby masking any shelter effect (Nuberg, 1998; Tibke, 1988). Despite the Munsell colour-code descriptions in the last paragraph of Section 2.2.3 $^{\text{Ch. 2}}$ indicating a sandier soil at 11.0 H (compared to 1.0 and 3.0 H), little variation in soil moisture was observed between each location.

Possibly the most important implication of the lack of soil moisture conservation effect in the sheltered zone was that there was subsequently no indication of a depletion of soil moisture resulting from the southern WoS3 windbreak. This conclusion, as well as the absence of surface tree roots beyond 0.5 H provided further evidence that the young *C. cunninghamiana* windbreak did not cause significant below-ground competition at 1.0 H.

The WoS3 soil-moisture levels were considered to be non-limiting for at least the initial four months of growth. The soil probes were installed in the final 2 weeks of this period of non-limiting soil moisture. During this period, two rain events caused the recharge peaks shown in Figure 1.2.10. The remaining period of growth at WoS3 was characterised by drier, hotter, and windier conditions. As the shelter effect was more likely to affect the conservation of soil moisture in conditions of high evaporative demand and limited soil water than in wetter conditions (Nuberg, 1998; Hough and Cooper, 1988), a potential soil moisture conservation effect was anticipated during the drier period at WoS3. Guyot *et al.* (1986) also reported that the response of sheltered crops was positive in wet conditions, but zero or negative when the water constraint became severe.

From the soil moisture probes, no soil moisture conservation effect was detected in this latter stage at WoS3. Perhaps the low water holding capacity of the sandy soil at WoS3 severely limited the scope for soil moisture variation levels during the drier period.

There are other situations where a shelter effect will not operate directly on soil moisture. For example, shelter may increase leaf temperature and thereby increase transpiration / unit of leaf area. Alternatively, transpiration may actually increase with a decrease in wind speed where the difference between stomatal and boundary layer conductance results in a water vapour gradient being much greater than the temperature gradient (Brenner, 1996). Hence for any given situation, soil water reserves may be either conserved or depleted in the sheltered zone (Rosenberg *et al.*, 1983). Generalised statements about the water-use efficiency mechanism cannot be made (Nuberg, 1998; Brenner, 1996).

From a closely spaced *Populus* and *Paulownia* windbreak network adjoining winter wheat (in the temperate, semi-moist monsoon region of China), Song and Wei (1991) reported a more positive shelter effect on soil moisture. Results showed that the shelter effect on the crop was indirect, and hence the physical effect of wind on the crop was not as important as the effect of shelter on soil moisture. From investigations of *Paulownia* / wheat intercropped fields in the same region, windbreaks influenced the energy balance of the crop such that the ratio of evapo-transpiration to soil moisture increased, resulting in a reduced water deficit compared to control plots (Wu and Dalmacio, 1991). Whatever the outcome, windbreaks increase water-use efficiency and thereby increase crop production (Rosenberg *et al.*, 1983).

Sheltered crops might use more water (if that extra water is available) because sheltered crops are more vigorous and have a greater Leaf Area Index (LAI) relative to unsheltered crops (Cleugh *et al.*, 1998; Kowalchuk and De Jong, 1995, and Rosenberg *et al.*, 1983). This would be likely to increase photosynthetic activity and hence water-use efficiency (Cleugh, 1998). The rapid early growth of sheltered plants may stimulate root development, enabling plants to access greater soil volume, and increase the water and nutrients available to the crop (Nuberg, 1998). The possible increase of water use in the sheltered zone of WoS3, relative to the exposed zones, may therefore have resulted in the consistent level of soil moisture recorded across each site. Increased sheltered crop yields may be more indicative of the overall water conservation benefit (Dickey, 1988).

3 PRELIMINARY CONCLUSIONS FOR BOTH SITES

3.1 Wind speed at both sites

The portable weather station data indicated a clear beneficial shelter effect from the northern *P. radiata* windbreak at ViS1 to prevailing north-westerly winds at ViS1 in winter, and from the southern *C. cunninghamiana* windbreak at WoS3 to prevailing south-easterly winds in spring and early summer. The shelter effect was best illustrated by the consistently reduced wind speeds in the leeward sheltered zone of each site and for each of the sampling periods. To improve the correlation of the shelter effect, the mild southerly winds at ViS1 (contaminating data comprising 27% of the total data recorded at ViS1) and mild northerly winds at WoS3 (contaminating data comprising 28% of the total data recorded at WoS3) were excluded for the prediction equations of the shelter effect at each site. The generally consistent reductions of the shelter effect at ViS1 and WoS3 by non-prevailing contaminating winds suggested the requirement of a series of parallel windbreaks at ViS1 to provide maximum shelter from both northerly winds and southerly winds.

As wind speed for each hour was the averaged value taken from six sampled wind speeds taken at 10-minute intervals, the magnitude of the recorded wind speeds were subdued compared to some of the momentary gusts of wind. From the gale force winds that occurred throughout the Western Cape Region from 16 October to 20 October 1999, exposed wind speeds recorded by the portable weather station at WoS3 ranged from 4.0 to 6.0 m / s. The averaged hourly wind speed of 5.0 m / s was therefore considered to be gale force.

3.1.1 ViS1 wind speed

During the first sampling period at ViS1 (from 15 June to 23 July 1999), one wind sensor was located at 1.0 H to the windward side of the windbreak, and the other wind sensor was located at 3.0 H to the leeward side of the windbreak. The windbreak resulted in a 32% wind speed reduction in the more sheltered 3.0 H zone, relative to the more exposed wind speed on the windward side. The exclusion of southerly winds had little effect on the wind speed reduction levels in the more sheltered 3.0 H zone. Therefore, the southerly winds had a negligible impact on the general shelter effect. According to this improved regression equation ($r^2 = 98\%$), a 5.0 m/s wind was predicted to be reduced by 30% in the sheltered zone, for this particular sampling period.

During the second sampling period at ViS1 (23 July to 14 September 1999), wind sensors were located at 3.0 and 11.0 H to the leeward side of the windbreak. The exclusion of southerly winds increased the wind speed reduction level from 39 to 47%, indicating that the southerly winds reduced the effectiveness of the general shelter effect by 8%. According to this improved regression equation ($r^2 = 97\%$), a 5.0 m/s wind was predicted to be reduced by 44% in the sheltered zone, for this particular sampling period.

During the third sampling period at ViS1 (17 August to 14 September 1999), wind sensors were located at 1.0, 3.0 and 11.0 H to the leeward side of the windbreak. The exclusion of southerly winds increased the wind speed reduction level from 43 to 49% at 3.0 H and from 42 to 46% at 1.0 H. Therefore, the southerly winds reduced the effectiveness of the general shelter effect by 6 and 4% at 3.0 and 1.0 H respectively. According to this improved regression equation ($r^2 = 93\%$), a 5.0 m/s wind was predicted to be reduced by 56% in the sheltered zone (1.0 to 3.0 H), for this particular sampling period.

3.1.2 WoS3 Wind speed

During the first sampling period at WoS3 (14 September and 12 October 1999), wind sensors were located at 1.0, 3.0, and 11.0 H to the lee of the southern windbreak. Despite the lack of strong southerly winds and the frequent occurrence of interfering northerly and north-westerly winds, a general shelter effect from southerly winds was observed. The exclusion of northerly winds increased the wind speed reduction level from 43 to 63% at 3.0 H and from 42 to 56% at 1.0 H. This indicated that the northerly winds reduced the effectiveness of the general shelter effect by 20 and 14% at 3.0 and 1.0 H respectively. According to the improved regression equation, a 5.0 m/s wind speed reduction was predicted to be 64 and 39% at 3.0 to 1.0 H respectively, for this particular sampling period. Caution is necessary concerning the predictions for this sampling period due to the poor correlation of the regressions at 1.0 to 3.0 H. Turbulence immediately behind the WoS3 windbreak might have been responsible for the slightly reduced shelter effect at 1.0 H, compared to 3.0 H at higher exposed wind speeds.

During the second sampling period at WoS3 (12 October and 9 November 1999), wind sensors were located at 3.0, 7.0, and 13.0 H to the lee of the southern windbreak. Severe south-easterly winds dominated this period, resulting in a greatly improved overall shelter effect, compared to the previous sampling period. Notably, the average hourly wind speed at 3.0 H dropped from 0.9 m / s in the previous sampling period at WoS3 to 0.8 m / s, despite the sharp increase in exposed wind speeds. The exclusion of northerly winds increased the wind speed reduction level from 27 to 32% at 7.0 H and from 67 to 73% at 3.0 H. Therefore, the northerly winds reduced the effectiveness of the general shelter effect by 5 and 6% at 7.0 and 3.0 H respectively. According to this improved regression equation ($r^2 = 94\%$), a 5.0 m/s wind speed reduction was predicted to be 28 and 64% at 7.0 to 3.0 H respectively, for this particular sampling period.

3.1.3 Extent of wind speed shelter

For ViS1 and WoS3, The similarly low wind speeds at 1.0 and 3.0 H to the lee indicated that the maximum level of shelter extended to at 3.0 or 4.0 H to the lee. The extent of the leeward shelter effect was indicated from the intermediate wind speeds recorded at 7.0 H for the second sampling period at WoS3. If wind speed reductions dropped from 73% at 3.0 H to 33% at 7.0 H, then it would be reasonable to suggest that the intermediate shelter effect extended to approximately 10.0 H. The characteristically severe winds in the Western Cape Region restricted the extent of shelter to a conservative level.

3.1.4 Windward shelter

A windward shelter effect at ViS1 and WoS3 was also evident. The reduction of the effectiveness of the shelter effect due to contaminating winds (opposite in direction to the prevailing winds) at 1.0 H was less than that at 3.0 H. The improved regression equations had less impact on the r^2 value for the 1.0 H data, compared to the respective 3.0 H data. This was due to reduced fluctuations of northerly wind speeds at 1.0 H, compared to 3.0 H.

3.2 Soil temperature at both sites

At WoS3, soil temperature probes were located at 3.0 and 11.0 H to the lee, from 14 September to 9 November 1999. The pronounced shelter effect was further illustrated when strong and sustained wind speeds at WoS3 caused leeward soil temperature increases of up to 4°C at 3.0 H, compared to 11.0 H. Subsequently the five days of consistent gale force winds produced the greatest temperature differences. High (but briefly occurring) wind speeds had little effect on the soil temperature differences. Increased water use efficiency was likely, provided that the increased temperatures attributed to reduced wind speeds did not exceed the thermal optimum levels for the sheltered crop species.

At ViS1, soil temperature probes were located at 3.0 and 11.0 H to the lee from 24 August to 14 September 1999. Strong winds did not occur on a sustained level at ViS1, resulting in little difference in soil temperatures on both sides of the ViS1 windbreak. Another contributing factor to the similar soil temperatures at ViS1 was the potentially highly sheltered conditions at the windward location (at crop height) due to the 1.0 m high fynbos at the northern boundary of the cleared area. Considering that the soil temperature probe was only 3.0 m from the fynbos 'windbreak', the soil temperature probe must be considered to have been well within the sheltered zone attributed by the fynbos. This probable fynbos shelter effect at crop level was not indicated by the windward wind speed data because the anemometer unit was positioned at 1.5 m above the ground, thereby being beyond the influence of the fynbos.

3.3 Soil moisture at both sites

At ViS1, soil moisture probes were located at 1.0, 3.0, and 11.0 H to the lee of the respective windbreak. By excluding a period of soil saturation, a clearer indication of a possible soil-moisture conservation effect emerged where there was a deviation of soil moisture content between 3.0 and 11.0 H following periods of recharge. Perhaps a sampling period with less rain might have produced a less interrupted trend of this soil-moisture conservation effect. Compared to 3.0 and 11.0 H, soil moisture content at 1.0 H was consistently higher. This may indicate a shelter effect from the windbreak intercepting radiation and thereby reducing evaporation and transpiration at 1.0 H, relative to distances further from the windbreak. This trend also indicated an absence of below-ground competition from the windbreak. The absence of surface roots beyond 0.5 H provided further evidence that the windbreak did not cause significant below-ground competition at 1.0 H.

At WoS3, soil probes located at 1.0, 3.0, and 11.0 H from the windbreak did not indicate that soil moisture was influenced by the shelter effect. Although this implied an absence of a soil moisture conservation effect, it also implied a negligible competition effect. Several factors may have contributed to the absence of a soil moisture conservation effect at WoS3:

1. The late occurrence of the prevailing winds

2. The low water holding capacity of the sandy soil at WoS3, therefore soil moisture levels were so low during the drier period that there was little scope for variation.

3. Sheltered crops might use more water (if that extra water is available) because sheltered crops are more vigorous compared to unsheltered crops. Increased sheltered crop yields may be more indicative of the overall water conservation benefit.

4 REFERENCES

Amjad M. and Khan N. (1988) The state of forestry in Pakistan. Forest Economics Branch, Pakistan Forest Institute Peshawar, Pakistan, 103 pp. In: Khan G. and Ehrenreich J. (1994) Effect of increasing distance from *Acacia nilotica* trees on wheat yield. Agrofor. Syst. 25: 23 - 29.

Banzhaf J., Leihner DE., Buerkert A. and Serafini PG. (1992) Soil tillage and windbreak effects on millet and cowpea: 1. Wind speed, evaporation and wind erosion. Agron. J. 84: 1056 – 1060.

Barker GL., Hatfield JL. and Wanjura DF. (1985) Cotton plant response to wind and water stress. Transactions of the ASAE 28 (1): 194 - 200. In: Cleugh HA., Miller JM. and Bohm M. (1998) Direct Mechanical effects of wind on crops. Agrofor. Syst. 41: 83 - 112.

Benzarti J. (1999) Temperature and water - use efficiency by lucerne (*Medicago sativa*) sheltered by a tree windbreak in Tunisia. Agrofor. Syst. 43: 95 - 108.

Benzarti J. (1989) Influence du brise - vent sur la production fourragere. In: Contribution a lÉtudie des Brise - vent en Tunisie et en Region Mediterranenne, Ann INRAT, pp. 138 - 145. In: Benzarti J. (1999) Temperature and water - use efficiency by lucerne (*Medicago sativa*) sheltered by a tree windbreak in Tunisia. Agrofor. Syst. 43: 95 - 108.

Bird PR., Bicknell D., Bulman PA., Burke SJA., Leys JF., Parker JN., Van Der Sommen FJ. and Voller P. (1992) The role of shelter in Australia for protecting soils, plants and livestock. Agrofor. Syst. 20: 59 - 86.

Bird PR. (1988) Financial gains of trees on farms through shelter. Proc. Internat. Forestry Conf. For the Australian Bicentary 1988. Aust. Forest Development Institute, Vol 2. In: Bird PR. (1998) Tree windbreaks and shelter benefits to pasture in temperate grazing systems. Agrofor. Syst. 41: 35 - 54.

Brandle JR., Johnson BB. and Akeson T. (1992) Field windbreaks; are they economical? J. Prod. Agric. 5 (3): 393 - 398.

Brenner AJ. (1996) Microclimatic modification in agroforestry. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Cleugh HA. and Hughes DE. (2000) The impact of shelter on crop microclimates: a synthesis of results from wind tunnel and field experiments. Unpublished.

Cleugh HA. (1998) Effects of windbreaks on airflow, microclimates and crop yields. Agrofor. Syst. 41: 55 - 84.

Cleugh HA., Miller JM. and Bohm M. (1998) Direct Mechanical effects of wind on crops. Agrofor. Syst. 41: 83 - 112.

Dickey GL. (1988) Crop water use and water conservation benefits from windbreaks. Agric. Ecosyst. Environ. 22 / 23: 381 - 392.

Doorenboos J. and Kassaam AH. (1980) Reponse des rendements a l'eau. Bull FAO d'Irrig et de drain, No. 33. In: Benzarti J. (1999) Temperature and water - use efficiency by lucerne (Medicago sativa) sheltered by a tree windbreak in Tunisia. Agrofor. Syst. 43: 95 - 108.

Guyot G., Delecolle R. and Ben Salem M. (1986) Brise - vent et rideaux abris avec référence particuliére aux zones séches. Conservation, Cahiers FAO, No. 15, 385 pp. In: Benzarti, J. (1999) Temperature and water - use efficiency by lucerne (*Medicago sativa*) sheltered by a tree windbreak in Tunisia. Agrofor. Syst. 43: 95 - 108.

Haigh H. (1994) Farm forestry. In: Forestry Handbook. Van der Sijde HA. (ed.) pp. 828 - 840.

Hodges L. and Brandle JR. (1996) Windbreaks: an important component in a plasticulture system. Hort. Technology 6: 177 - 181.

Hough and Cooper (1988) The effects of shelter for cereal crops in an exposed area of Cleveland, NE England. Soil Use and Management 4 (1): 19 - 22. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Jaffe MJ. (1976) Thigmomorphogenesis: a detailed characterisation of the response of beans (*Phaseolus vulgaris* L.) to mechanical stimulation. Z Pflanzenphysiol 77: 437 - 453. In Cleugh HA., Miller JM. and Bohm M. (1998) Direct Mechanical effects of wind on crops. Agrofor. Syst. 41: 83 - 112.

Jensen AM. (1993) Shelterbelts versus screen plantations in the sahelian zone. In: Windbreak and Agroforestry, pp 171 - 173. Forth Intern Symp, Hedeselskabet (Denmark), July 26 - 30. In: Benzarti J. (1999) Temperature and water - use efficiency by lucerne (*Medicago sativa*) sheltered by a tree windbreak in Tunisia. Agrofor. Syst. 43: 95 - 108.

Kowalchuk TE. and De Jong E. (1995) Shelterbelts and their effect on crop yield. Can. J. Soil Sci. 75: 543 - 550.

Marshall JK. (1967) The effect of shelter on the productivity of grasslands and field crops. Field Crop Abstracts 20: 1 - 14. In: Bird PR. (1998) Tree windbreaks and shelter benefits to pasture in temperate grazing systems. Agrofor. Syst. 41: 35 - 54.

Mitchell CA., Severson CJ., Woot JA. and Hammer PA. (1975) Seismomorphogenic regulation of plant growth. J. Am. Soc. Hort. Sci. 100: 161 - 165. In: Cleugh HA., Miller JM. and Bohm M. (1998) Direct Mechanical effects of wind on crops. Agrofor. Syst. 41: 83 - 112.

Munsell Color Co. (1975) Munsell Soil Color Charts. Macbeth Div. Kollmorgen Corp. Maryland, USA.

Myburgh J. and Viljoen GK. (1979) Protection of deciduous fruit trees against wind. The Deciduous Fruit Grower, March. pp. 72 - 78.

Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Pienaar P. (1987) Wind protection in orchards: effect on growth, production and fruit quality. Deciduous Fruit Grower, August. pp. 291 - 295.

Pretzechel M., Bohme G. and Krause H. (1991) Effects of shelterbelts on crop yield. Feldwirtschaft 32(5): 229 - 231. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Puri S., Singh S. and Khara A. (1992) Effect of windbreak on the yield of cotton crop in semiarid regions of Haryana. Agrofor. Syst. 18: 183 - 195.

Rocheleau D., Weber F. and Field-Juma A. (1988) Agroforestry in dryland Africa. ICRAF. Nairobi, Kenya, 311 pp.

Rosenberg NJ., Blad BL. and Verma SB. (1983) Microclimate, the biological environment. John Wiley and Sons, New York, pp. 595. In: Davis JE. and Norman JM. (1988) Effects of shelter on plant water use. Agric. Ecosyst. Environ. 22 / 23: 393 - 402.

Sanchez PA. (1995) Science in agroforestry. Agrofor. Syst. 30: 5 - 55.

Schroeder W. (1988) Planting and establishment of shelterbelts in humid severe winter regions. Agric. Ecosyst. Environ. 22 / 23: 441 - 464.

Song ZM. and Wei L. (1991) The correlation between windbreak influenced climate and crop yield. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Sun D. and Dickinson GR. (1997) Early growth of six native Australian tree species in windbreaks and their effect on potato growth in tropical northern Australia. For. Eco. Man. 95: 21 - 34.

Sun D. and Dickinson GR. (1994) A case study of shelterbelt effect on potato (*Solanum tuberosum*) yield on the Atherton Tablelands in tropical north Australia. Agrofor. Syst. 25: 141 - 151

Tibke G. (1988) Basic principles of wind erosion. Agric. Ecosyst. Environ. 22 / 23: 103 - 122.

Ujah JE. and Adeoye KB. (1984) Effects of shelterbelts in the Sudan savanna zone of Nigeria on microclimate and yield of millet. Agric. For. Meteorol. 33: 99 - 107. In: Ritchie KA. (1988) Shelterbelt plantings in semi-arid areas. Agric. Ecosyst. Environ. 22 / 23: 425 - 440.

Van Gardingen PR. and Grace J. (1991) Plants and wind. Adv. Bot. Rese. 18: 189 - 253. In: Hodges L. and Brandle JR. (1996) Windbreaks: an important component in a plasticulturesystem. Hort Technology 6: 177 - 181.

Wu YY. and Dalmacio RV. (1991) Energy balance, water use and wheat yield in a *Paulownia* - wheat intercropped field. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

CHAPTER 3

AN INVESTIGATION OF CROP VARIATION RELATIVE TO THE DISTANCE FROM WINDBREAK, IN THE WESTERN CAPE REGION OF SOUTH AFRICA

The purpose of this chapter was to investigate crop variation in relation to the distance from windbreaks at each of the five research sites. The northern *Pinus radiata* windbreaks at Villiersdorp Site 1 (ViS1) and Saron Site 1 (SaS1) were suspected to provide crop shelter from prevailing north-westerly winds in winter. The southern *Casuarina cunninghamiana* windbreaks at three Wolseley sites (WoS1, WoS2, and WoS3) were suspected to provide crop shelter from prevailing south-easterly winds in spring and summer. Crops were planted at various distances from selected windbreaks at WoS1 (triticale), WoS3 (barley), and ViS1 (potatoes and barley). Existing crops of wheat and pear trees were used for SaS1 and WoS2 respectively.

1. VILLIERSDORP SITE 1 (ViS1)

1.1 Method

1.1.1 Regional description

Villiersdorp Site 1 (ViS1) was located 10 km west of Villiersdorp (longitude: 19°11′E, lattitude 33°59′S, altitude: 330 m), on the "Mooi Water" farm of Francois du Toit. Plate 1.1 in Section 3.2 $^{\text{Ch. 1}}$ illustrates the location of ViS1 in the Western Cape Region.

Table 1.1.1 in Section 1.2.2 $^{\text{Ch. 2}}$ shows the summarised long term and 1999 data collected from the "Chiltern Dam Wall" DWAF weather station, located 10 km south-west of ViS1. However, the Mooi-Water farm experienced a microclimate quite different to the climatic data presented by the DWAF weather station. The big difference between the locations was the absence of the prevailing south-easterly winds at the Mooi-Water farm during spring and summer, attributed to the presence of a nearby mountain to the south that effectively blocked out such winds. Winter and spring north-westerly winds were the prevailing winds at Mooi-Water, caused by wind being pushed through the Franschhoek Pass.

The climatic patterns at the DWAF weather station were more typical for the Western Cape Region. The average yearly long-term wind speed was 224.3 km / day, which was higher than any other project site. This was especially the case from May to December, attributed to the severe north-westerly winds in winter and spring, and also severe south-easterly winds in spring to summer. The average daily maximum temperature was 27.1°C for the hottest month (January) and the average daily minimum temperature for the coolest month (July) was 6.0°C. The site was in a temperate winter rainfall area, with June having the highest average monthly rainfall (177.9 mm), and January having the lowest average monthly rainfall (17.2 mm). Data for total evaporation and Relative Humidity (RH) are also included in Table 1.1.1 in Section 1.2.2 $^{\text{Ch. 2}}$.

1.1.2 Site description

An aerial view of ViS1 is illustrated in Plate 2.1.1, and a profile view of the northern windbreak with adjoining crop strips (and weather station) is shown in Plate 1.2 in Section 3.2 $^{\text{Ch. 1}}$. This site had a *P. radiata* windbreak with an average effective height (H) of 7.0 m, adjoining the north and south borders of a vacant block of land. Distance between the two windbreaks was 170.0 m (24.2 H). The windbreaks were each orientated in a north-easterly direction. The 3-year old windbreak was double rowed and the trees were spaced 1.0 m apart from each other in a non-staggered pattern.

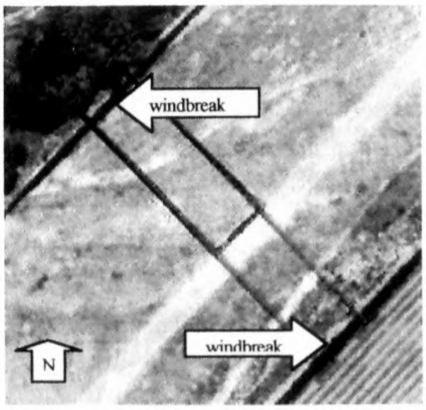

Plate 2.1.1 Aerial view of ViS1. Prevailing winds were north-westerly. Scale 1:4000.

The northern windbreak was pruned to a height of 2.0 m. Since gaps in the lower section of the windbreak can cause serious damage to crops due to excessive turbulence (Rocheleau *et al.*, 1988), 50.0 m of netting of 40% porosity was necessary to seal gaps in the windbreak. Gaps were minimal following the installation of the netting. Access tracks of approximately 4.0 m width were present on the northern and southern side of the northern windbreak. Therefore, the minimum distance that the crops were established beside the northern windbreak was 5.0 m (0.7 H). Fynbos, that exceeded a height no more than 1.5 m, existed between the two windbreaks and immediately to the north of the northern windbreak.

An initial soil investigation on 12 January 1999 provided an insight into the soil variations across the vacant block of land. This investigation involved a rapid collection of surface soil samples spaced at 20 m x 20 m from each other. The most homogenous 20 m wide section between both windbreaks was thereby selected for the site. The most southerly 40 m of vacant land (perpendicular to the northern windbreak) was excluded from the analysis as the soil in this region appeared much sandier compared to the more northerly areas.

Soil pits were excavated on 28 September 1999 at four central points running from north to south, and each to a depth of 0.8 to 1.0 m. Refer to Paragraph 4 of Section 1.1.3 $^{\text{Ch. 2}}$ for a more detailed description of the soil profiles at ViS1. Using Munsell colour codes (Munsell Color Co., 1975), each soil pit was described:

- Soil Pit 1 (1.0 H to the windward side of the windbreak). Classification: Tukulu 2110

- Soil Pit 2 (3.0 H to the leeward side of the windbreak). Classification: Pinedene 2100, transition to Constantia 1100

- Soil Pit 3 (7.8 H to the leeward side of the windbreak). Classification: Dundee (wet) 1210

- Soil Pit 4 (12.8 H to the leeward side of the windbreak). Classification: Pinedene 2100, transition to Tukulu 2110.

Soil was also sampled on 1 October 1999 to a depth of 10 to 20 cm at 1.0, 1.7, 2.4, 3.6, 5.1, 7.3, 10.2, and 13.7 H to the leeward side and 1.0 H to the windward side of the northern windbreak. Each collected sample was a composition of soil collected from three points of a specific distance from the southern windbreak. These points were located in the central region of the site, and 10.0 m apart from each other. Each composite sample was sealed in a labelled paper bag, and then air-dried for 1 week. The dried soil was then analysed for the content of available N, exchangeable cations (Na+, Ca++, P++, K+), and pH. Munsell colour-code descriptions for each soil sample (in both the wet and dry state) provided further information concerning soil homogeneity across the site.

1.1.3 Experimental design

1.1.3.1 General design

The general shape of the design was a 22.0 m wide block extending 140.0 m south and 10 m north of the northern windbreak. Plate 2.1.2 illustrates the experimental crop design for ViS1. To minimise the amount of area included in the experiment, 22.0 m long strips (each 3.0 m wide) were designated at specific distances parallel to the windbreak. Strips were designated at 5.0 to 8.0, 10.0 to 13.0, 15.0 to 18.0, 23.0 to 26.0, 34.0 to 37.0, 48.0 to 51.0, 76.0 to 79.0, and 94.0 to 97.0 m (1.0, 1.7, 2.4, 3.6, 5.1, 7.3, 11.1, 13.7 H respectively) from the leeward side of the northern windbreak. An extra strip was designated 5.0 to 8.0 m (1.0 H) to the northern (windward) side of the northern windbreak. Areas between strips and also the area extending 40.0 m southwards of the most southern strip remained fallow and were excluded from the experimental design.

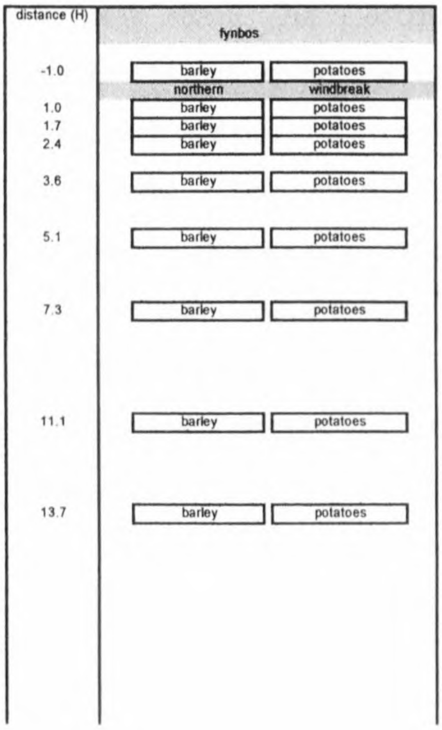

Plate 2.1.2 Experimental crop design for ViS1

Wind sensitive fodder barley (*Hordeum vulgare*) was sown in the western half of each of the nine strips, and potatoes (*Solanum tuberosum* L. cultivar Lady Rosetta, variety Lisita) were planted in the eastern half of each strip.

1.1.3.2 Design for barley crop

The inner 10.0 m of each strip of barley was intended to contain 10 replicates, each plot being 1.0 m x 1.0 m and located in the central region of the replicate. Noting early damage to the crop, a barley damage assessment (for main stem collapse) took place on 25 June 1999, 2 weeks after sowing and 1 week after emerging from the soil. A 30 cm x 30 cm sub-plot was placed in the central region of each of the ten plots of each strip. To calculate the proportion (%) of damaged barley in each transect, the number of damaged barley plants and the number of total barley plants were recorded. Damage status denoted complete levelling of the barley plants main stem, and a non-damaged status denoted an upright main stem.

During this assessment, the total number of barley plants fluctuated considerably from plot to plot. Plots with higher numbers of plants (as high as 100) had the potential to show a much higher competition effect between individual plants, compared to transects with lower numbers of plants (as low as 30). This competition effect would become more pronounced as the crop aged, and may have ultimately interfered with the actual windbreak effect. Air movement through different densities may also have varied. Therefore to improve the level of standardisation across the site, new plots were selected so that each contained between 30 and 40 plants, being consistently spread throughout the transect area. These transects were pegged on 9 and 10 July 1999 in preparation for a second barley damage assessment on 19 July 1999. There were three damage classes used in this analysis. Class-0 damage entailed intact plants, Class-1 damage entailed peripheral damage to plants (the lower leaves being pushed down onto the ground), and Class-2 damage entailed severe damage (levelling of the main stem). Proportions of each class in each transect were recorded.

Shortly following this assessment, some light grazing by guinea-fowl was noted, hence the inner 8 m of each of the 9 strips was fenced with chicken wire to ensure no grazing of the barley. The outer 3 m of each strip remained unprotected from guinea fowl, and was therefore excluded from any further analysis. This resulted in the exclusion of Replicate 9 and 10 from each crop strip.

On 15 and 17 November 1999, the barley plots were harvested at ground level and placed in labelled paper bags. Each sample had all grain heads cut (directly below the lowest grain on the head) and bagged separately from leaf and stem^{mass}. Samples were then oven dried at 100°C and weighed for total head^{mass}, leaf and stem^{mass}, and above-ground^{mass}. Grain head number, average head^{mass}, and transformed (square root) proportion of total head^{mass} from above-ground^{mass} was also recorded.

1.1.3.3 Design for potato crop

For each strip, potatoes were planted 25 cm apart, in four rows that were 80 cm apart from each other. The inner two rows were intended for sampling, and the outer two rows acted as buffer. From each of the inner two rows, the inner 32 plants were designated in eight plots each, so that each plot contained four plants. Therefore, there were 16 plots replicated in each of the eight crop strips.

Immediately before destructive sampling took place, the length of the most southerly stem and the length of the most northerly stem were measured for each plant within each plot. This was aimed to provide information concerning the effect of wind on the structural above-ground symmetry of potato plants. The data for each of the four plants in each plot were averaged.

Each plot was then harvested for both above-ground^{mass} and tuber (below-ground)^{mass}. For above-ground^{mass}, each harvested plot sample was bagged, oven-dried at 100°C, and weighed. Excavation of potato tubers was thorough. Tubers were immediately washed, allowed to dry over-night, and weighed for fresh tuber^{mass}. Each plot of potato tubers was then classified into two classes according to width. "Small" tubers were less than 4 cm in diameter, and "large" tubers were over 4 cm in diameter.

1.1.4 Site preparation

On 9 June 1999, the area south of the northern windbreak (24.0 m wide and 100.0 m long) and the area north of the northern windbreak (24.0 m wide and 10.0 m long) was ripped and then ploughed several times to ensure that the fynbos was mulched into the soil. No herbicide was applied to this site. On the same day, the 11 strips were pegged and then once again ploughed by a tractor for soil preparation. Fertilizer (400 kg / ha super-phosphate (10.5% P), 100 kg / ha 2:3:2 (22), and 100 kg / ha LAN (28% N)) was applied evenly by hand to each cultivated strip. Barley (80 kg / ha) was sown in the eastern half of each strip. Fertilizer and barley were then ploughed into the soil by a tractor. All of the above site preparation was done on 9 June 1999. A fertilizer supplement of 130 kg / ha LAN (28%) was applied on 26 August 1999, followed by a further application of 300 kg / ha LAN (28%) on 16 September 1999.

The remaining unplanted westerly half of each strip was planted with potatoes on 10 June 1999. For each strip, potatoes were planted 25 cm apart, in four rows that were 80 cm apart. Potatoes were of consistent size. Heavy rains on 14 June 1999 ensured good initial growing conditions. On 26 August 1999, a broadcast supplement of 100 kg / ha 2:3:2 was added to each crop strip. All potato plants were diagnosed with the fungal disease known as Late Blight (*Phytophthora infestans*) on 6 September 1999. The entire potato crop was immediately sprayed with 2.5 L / ha Bravo 500 (chlorothalonil as the active ingredient, making up 500 g / L of the fungicide), and sprayed again on 10 September 1999. The potato crop was also sprayed with 0.6 L / ha insecticide (chlorpirifos as the active ingredient, making up 480 g / L of the fungicide) on 8 September 1999 to eliminate millipedes that were beginning to graze upon the leaves.

Potatoes showed no evidence of being grazed until 25 August 1999. Several potato plants were extensively grazed by buck, which prompted immediate fencing of all potatoes. This was sufficient until baboons and porcupines began rooting up a small number of potato plants on 14 September 1999. Due to the combined adverse conditions of animal, insect, and fungal damage, and rapidly decreasing moisture content in the soil, sampling began one month earlier than planned, on 15 September 1999.

1.1.5 Wind speed and soil moisture measurements

The weather station operated from 15 June to 14 September 1999 to obtain information concerning variations of wind speed, soil temperature, and soil moisture content in relation to the distance of the northern windbreak. Details were discussed in Section 1 $^{\text{Ch. 2}}$.

Soil samples were collected at specific distances from the southern windbreak on 11 July 1999, to provide an insight into the variation of soil moisture content across the site. Samples were collected at 15 to 20 cm below the soil surface. Sampled soil was immediately sealed tightly in a labelled tin. Each tin was weighed, and weighed again following oven drying with lids loosened (at 100°C for 24 hours). Tins were then emptied and weighed. Calculations were made using the following formula:

$$\text{MC (\%)} = (\text{undried soil}^{\text{mass}} - \text{dried soil}^{\text{mass}}) / \text{dried soil}^{\text{mass}} \text{ X } 100$$

1.1.6 Windbreak porosity

Windbreak porosity was estimated using two photographs of 3 m x 3 m samples for each windbreak. Each image was scanned and then posturised by computer. The porosity was calculated using an image digitalisation programme that calculated the number of darker pixels compared to lighter pixels. The porosity of the two images from each windbreak was then averaged.

1.1.7 Statistical methods

Crop data and soil moisture, wind speed, and soil temperature data were analysed by Analysis of Variance (ANOVA), and Chi-Square tests where appropriate. Statistical analysis was done with SAS (SAS Institute Inc., 1985).

1.2 Results

1.2.1 Climatic and soil data

Table 2.1.1 summarises the Munsell colour-code (Munsell Color Co., 1975) descriptions for various distances to the lee of the ViS1 windbreak. The average porosity of the northern ViS1 windbreak (above 2.0 m height) was calculated to be 40%.

Table 2.1.1 Summary of Munsell colour-code descriptions, for various distances (H)* from the northern ViS1 windbreak.

distance (H)	*wet Munsell colour code description*	*dry Munsell colour code description*
-1.0	10YR42 (dark greyish brown)	10YR62 (light brownish grey)
1.0	10YR42 (dark greyish brown)	10YR61 (grey)
1.7	10YR42 (dark greyish brown)	10YR61 (grey)
2.4	10YR42 (dark greyish brown)	10YR61 (grey)
3.6	25YR52 (greyish brown)	25YR62 (light brownish grey)
5.1	10YR41 (dark grey)	10YR61 (grey)
7.3	10YR41 (dark grey)	10YR61 (grey)
11.1	10YR42 (dark greyish brown)	10YR61 (grey)
13.7	10YR42 (dark greyish brown)	10YR61 (grey)

* Effective tree height (H) was estimated to be 7.0 m. A negative tree height indicates a location on the windward side of the windbreak. A positive tree height indicates a location on the leeward side of the windbreak.

Soil nutrient variation across the site was consistent, as indicated by the soil analysis described in Table 2.1.1. References to threshold levels for barley and potatoes were insufficiently detailed, so estimates were developed from personal communication with Prof. Andre Agenbag and Mnr. Jan Lambrechts. The pH (KCl) at all distances (pH ranging from 3.8 to 4.2) was consistently below the optimum level for potatoes (pH = 4.5) and especially so for barley (pH = 5.0 to 6.0). P levels were possibly slightly limiting (below 25 mg / kg) for 1.0 H to the windward side (21 mg / kg) for potatoes and barley.

The Ca : Mg ratio was below the optimum level (4.0 to 6.0 for both potatoes and barley) at 1.0 H on the windward side (3.4) and 1.0 H (3.6) and 5.1 H (3.6) to the leeward side. K (% of S), alkaline resistance, Ca, Mg, and Na were not limiting at any distance across the site) for both potatoes and barley. Available N levels were highly variable, due to the high levels of LAN fertiliser that were applied to the crop strips a month before soil sampling took place. Therefore, data for available-N was of little use, but consistent levels of fertiliser application and also the absence of N-deficiency symptoms in each crop strip suggested that available-N was not limiting.

Munsell-colour codes across the site indicated a lighter and sandier band soil at 3.6 and 5.1 H to the lee due to a drainage line that can be seen in the aerial photograph (Plate 2.1.1 in Section 1.1.3 $^{\text{Ch. 2}}$). The darkest soils, occurring at 1.0 H on the windward side and 1.0, 1.7, and 13.7 H to the leeward side, indicated higher levels of organic matter and soil structure, compared to the remaining distances across the site.

1.2.2 Barley damage

1.2.2.1 Damage to 2-week old barley

For the crop damage assessment for the 2-week old barley, the computed value for the Chi-square test of independence indicated that the differences of damage between distances were significant ($X^2 < 0.05$). Using the same test of independence, the computed values comparing the independence of each category of damage was found to be significant ($X^2 < 0.05$). Figure 2.1.1 illustrates the averaged distribution of damage to the 2-week old crop, in relation to the distance from the northern ViS1 windbreak. Plates A1.1 and A1.2 in Section 6 $^{\text{Ch. 3}}$ illustrate the visual difference in levels of barley damage for the sheltered zone (at 2.0 H to the lee) and the unsheltered zone (at 13.7 H to the lee) respectively. Percentages are averages of replications.

No damage was observed at 1.0, 1.7, 3.6, and 5.1 H to the lee. A negligible level of damage occurred at 2.4 H (1%) to the lee. Therefore, generally no damage was recorded from 1.0 to 5.1 H to the lee. Levels of damage increased at 7.3 and 11.1 H to the lee (7 and 9% respectively) and 1.0 H to the windward side (12%). The highest levels of damage occurred at 13.7 H (25%) to the lee, which was the maximum distance sampled from the windbreak.

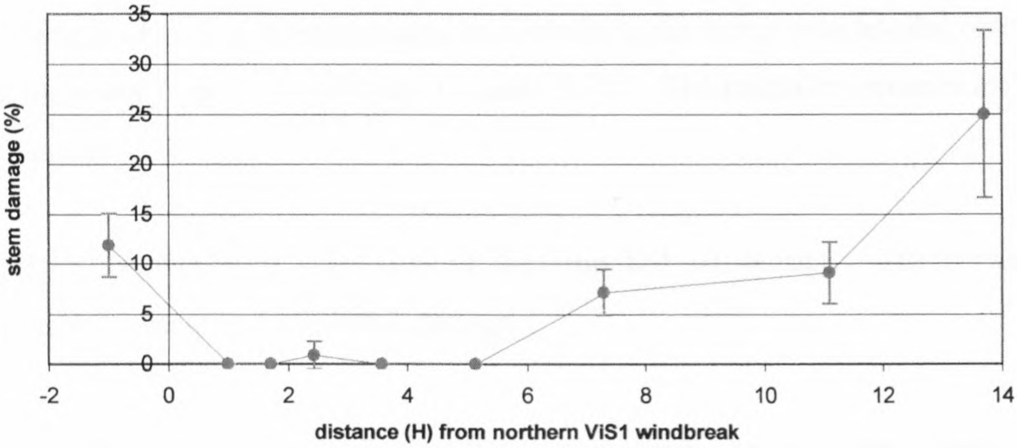

Figure 2.1.1 Averaged distribution of damage to the 2-week old crop, in relation to the distance from the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. Error bars indicate the level of the 95% confidence interval for each treatment. Data points have been joined to enhance visual presentation.

1.2.2.2 Damage to 6-week old barley

With continued barley crop damage following this initial assessment, a second assessment was done for 6-week old barley. Once again a significant shelter effect due to the windbreak was indicated. The computed value for the Chi-square test of independence indicated that the differences of damage between distances were significant ($X^2 < 0.05$). Using the same test of independence, the computed values comparing the independence of each category of damage was found to be significant ($X^2 < 0.05$). Figure 2.1.2 illustrates the averaged distribution of damage to the 6-week old crop, in relation to the distance from the northern ViS1 windbreak. Percentages are averages of replications.

Class-0 damage (denoting no crop damage) was observed from 1.0 to 2.4 H to the lee. At 3.6 H, most of the crop remained undamaged with rare instances (2%) of Class-1 damage (denoting damage whereby the lower leaves were pushed onto the ground).

Class-1 damage increased to 33 and 100% at 5.1 and 7.3 H respectively. No Class-0 damage occurred beyond 5.1 H.

Class-2 damage (denoting severe damage, whereby the barley stems were levelled onto the ground, increased from 35 to 98% at 11.1 and 13.7 H. The remaining proportions had Class-1 damage.

At 1.0 H to the windward side, 78% of the crop had no damage. The remaining proportion at this location had Class-1 damage.

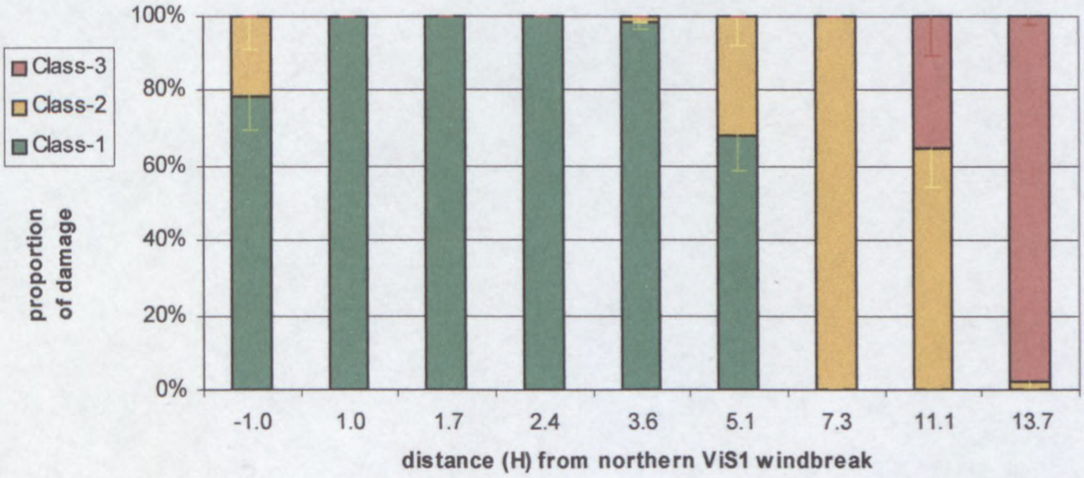

Figure 2.1.2 Averaged distribution of damage to the 6-week old barley crop, in relation to the distance from the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. Error bars indicate the level of the 95% confidence interval for each treatment.

1.2.3 Barley yields

Soon after assessing the 2-week old barley crop, the barley at 3.6 H to the lee showed a much slower growth rate compared to the other crop strips. This was attributed to the very poor soil type that occurred in this localised area, which was indicated in the Munsell

1.2.3 Barley yields

Soon after the 2-week old barley assessment, the barley at 3.6 H to the lee showed a much slower growth rate compared to the other crop strips. This was attributed to the very poor soil type that occurred in this localised area, which was indicated in the Munsell colour-code descriptions in Table 2.1.1 in Section 1.2.1$^{\text{Ch. 3}}$. Therefore, the barley crop strip at 5.1 H to the lee was omitted from any further analysis. Although the soil at 3.6 H had the same Munsell colour code described for the soil at 5.1 H, the barley at the former location experienced a much less adverse soil effect. The soil effect at 5.1 H was so localised that the potato strip at the same distance experienced no adverse effect. Table 2.1.2 summarises the means of grain head number, total head$^{\text{mass}}$, average head$^{\text{mass}}$, above-ground$^{\text{mass}}$, leaf and stem$^{\text{mass}}$, and transformed proportion of total head$^{\text{mass}}$ from above-ground$^{\text{mass}}$, at various distances from the northern ViS1 windbreak. Yields are given as averages.

Table 2.1.2 Summary of the means* of grain head number, total head$^{\text{mass}}$, average head$^{\text{mass}}$, above-ground$^{\text{mass}}$, leaf and stem$^{\text{mass}}$, and transformed (square root) proportion of total head$^{\text{mass}}$ from above-ground$^{\text{mass}}$, at various distances (H)** from the northern ViS1 windbreak.

distance (H)	head no.	total head$^{\text{mass}}$ (g)	average head$^{\text{mass}}$ (g)	above-ground$^{\text{mass}}$ (g)	leaf and stem$^{\text{mass}}$ (g)	transformed proportion of head$^{\text{mass}}$ (g)
-1.0	29.6_{a}	8.11_{a}	0.28_{a}	38.50_{a}	31.10_{a}	0.497_{a}
1.0	10.0_{bc}	3.92_{cd}	0.19_{a}	31.79_{a}	29.33_{a}	0.195_{bc}
1.7	25.4_{a}	6.19_{abc}	0.24_{a}	35.78_{a}	29.58_{a}	0.447_{a}
2.4	27.1_{a}	6.86_{ab}	0.25_{a}	35.36_{a}	28.50_{a}	0.474_{a}
3.6	20.5_{ba}	3.76_{bcd}	0.19_{a}	22.36_{b}	18.64_{b}	0.454_{a}
7.3	12.0_{bc}	2.59_{cd}	0.17_{a}	18.63_{b}	16.04_{b}	0.344_{ab}
11.1	8.8_{c}	2.88_{cd}	0.26_{a}	20.11_{b}	17.58_{b}	0.335_{ab}
13.7	3.3_{c}	0.90_{d}	0.21_{a}	20.59_{b}	19.80_{b}	0.176_{c}

* Means with the same subscript were not significantly different using the ANOVA method. Subscripts relate to respective columns only.

** Effective tree height (H) was 7.0 m. A negative tree height indicates a location on the windward side of the windbreak. A positive tree height indicates a location on the leeward side of the windbreak.

Distance from the northern windbreak had a significant effect ($p < 0.05$) on grain head number. Distance from the windbreak also had a significant effect ($p < 0.05$) on the transformed (square root) proportion of total head$^{\text{mass}}$ from the above-ground$^{\text{mass}}$. Yields for total head^{mass}, average head^{mass}, above-ground^{mass}, and leaf and stem^{mass} were not significantly effected ($p > 0.05$) by distance from the windbreak.

Figure 2.1.3 illustrates the averaged variation of head number, in relation to the distance from the northern ViS1 windbreak. Head number was significantly highest at 1.0 H to the windward side and 1.7 and 2.4 H to the lee (25.4 to 29.6 heads), and significantly lowest at 11.1 and 13.7 H to the lee (8.8 and 3.3 heads respectively).

A similar trend occurred for the transformed proportion of total grain^{mass} from the above-ground^{mass}, where significantly higher proportions occurred at 1.0 H to the windward side and 1.7, 2.4, and 3.6 H to the lee (0.447 to 0.497), and a significantly lower proportion occurred at 13.7 H to the lee (0.176). Figure 2.1.4 illustrates the averaged variation of the proportion of head^{mass} from total^{mass}, in relation to the distance from the northern ViS1 windbreak.

Although not significant, trends for total head^{mass}, above-ground^{mass}, and leaf and stem^{mass} were similar to the significant trends described above. The trend for average head^{mass} was the only exception to this general trend.

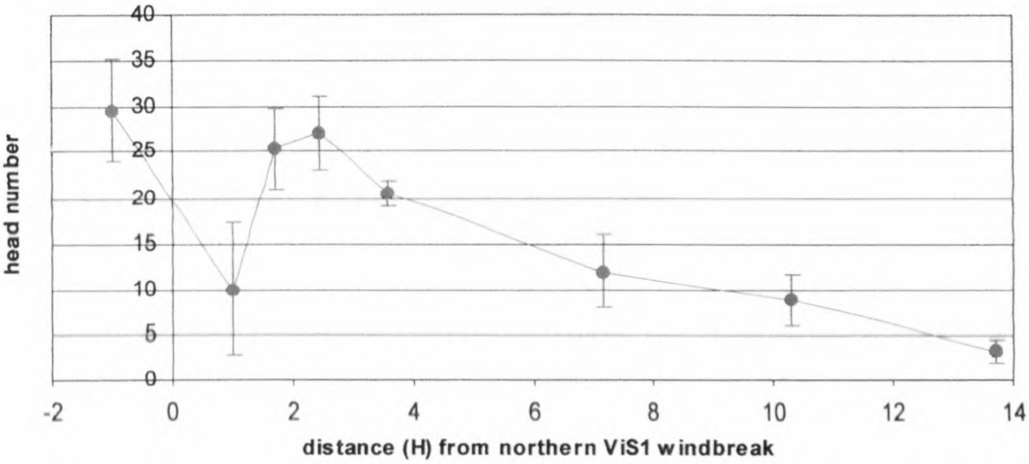

Figure 2.1.3 Averaged variation of barley head number, in relation to the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. Error bars indicate the level of the 95% confidence interval for each treatment. Data points have been joined to enhance visual presentation.

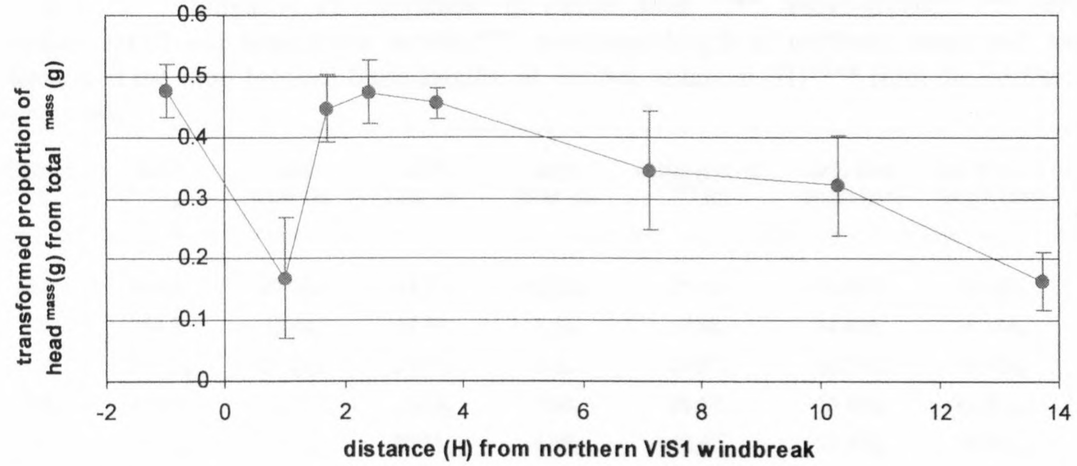

Figure 2.1.4 Averaged variation of the proportion of head^{mass} from total^{mass}, in relation to the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. Error bars indicate the level of the 95% confidence interval for each treatment. Data points have been joined to enhance visual presentation.

1.2.4 Potato yields

The potatoes in the strip that were located at 7.3 H from the northern windbreak quickly rotted due to an unexpectedly high level of waterlogging. The area affected was so localised that the barley on the same strip experienced no waterlogged conditions. Table 2.1.3 summarises the means of potato tuber^{mass}, total tuber number, small tuber number, large tuber number, and above-ground^{mass}, maximum length of northerly stems and southerly stems, and the ratio between these stem lengths at various distances from the northern ViS1 windbreak. Yields are given as averages.

Table 2.1.3 Summary of the means* of potato tuber^{mass}**, above-ground^{mass}** total tuber number, small and large tuber number***, maximum length of northerly stems and southerly stems, and the ratio between these lengths, at various distances (H)**** from the northern ViS1 windbreak.

distance (H)	tuber ^{mass} (g)	total tuber no.	small tuber no.	large tuber no.	above-ground ^{mass} (g)	north stem length (cm)	south stem length (cm)	south / north stem ratio
-1.0	493.8_a	27.19_{ab}	14.31_c	12.88_a	21.40_b	15.307_a	16.697_a	1.121_a
1.0	254.8_e	18.44_c	14.69_c	3.75_c	17.38_c	14.461_a	14.174_{bc}	0.997_a
1.7	373.8_{cb}	27.13_{ab}	21.81_a	5.3_{bc}	21.57_c	14.310_a	14.734_b	1.043_a
2.4	415.8_b	30.13_a	23.19_a	6.94_b	31.27_a	15.359_a	15.395_{ab}	1.017_a
3.6	329.4_{cde}	24.88_b	20.81_{ab}	4.06_c	16.87_c	12.479_b	13.056_{cd}	1.083_a
5.1	341.8_{cd}	27.00_{ab}	23.19_a	3.81_c	16.12_c	12.748_b	13.100_{ed}	1.043_a
11.1	291.6_{de}	20.69_c	17.56_{bc}	3.13_c	11.88_d	10.297_c	11.141_{ef}	1.128_a
13.7	313.7_{cde}	19.75_c	13.00_c	6.75_b	18.65_{bc}	10.516_c	13.281_f	1.306_b

* Means with the same subscript were not significantly different using the ANOVA method. Subscripts relate to respective columns only.

** Potato tuber^{mass} (g) denotes fresh^{mass} (g), and above-ground^{mass} (g) denotes oven-dried^{mass} (g)

*** Small tubers denote tubers <4cm diameter, and large tubers denote tubers >4cm diameter.

**** Effective tree height (H) was estimated to be 7.0 m. A negative tree height indicates a location on the windward side of the windbreak. A positive tree height indicates a location on the leeward side of the windbreak.

Distance from the northern windbreak had a significant effect ($p < 0.05$) on tuber^{mass}, above-ground^{mass}, total tuber number, small tuber number, large tuber number, south stem length, and north stem length. A significant interaction between distance and replicates ($p < 0.05$) was also recorded for the latter.

Figure 2.1.5 illustrates the averaged variation of the total tuber number, in relation to the ViS1 windbreak. Total tuber number was significantly highest ($p < 0.05$) at 2.4 H to the lee (30.1 tubers), and significantly lowest ($p < 0.05$) at 1.0, 11.1, and 13.7 H to the lee (18.4 to 20.7 tubers).

Small tuber number was generally significantly highest ($p < 0.05$) between 1.7 and 5.1 H to the lee (20.8 to 32.2 tubers), and significantly lowest ($p < 0.05$) at 1.0 H on the windward side and 1.0 and 13.7 H to the lee (13.0 to 14.7 tubers).

Large tuber number was significantly highest ($p < 0.05$) at 1.0 H to the windward side (12.9 tubers) and followed by yields at 2.4 and 13.7 H to the lee (6.7 to 6.9 tubers).

Large tuber number was significantly lowest ($p < 0.05$) at 1.0, 3.6, 5.1, and 11.1 H to the lee (3.1 to 4.1 tubers).

Figure 2.1.6 illustrates the averaged variation of potato tuber $^{\text{mass}}$, in relation to the ViS1 windbreak. Tuber$^{\text{mass}}$ was significantly highest ($p < 0.05$) at a distance of 1.0 H to the windward side (493.8 g). Tuber$^{\text{mass}}$ was also significantly high ($p < 0.05$) at a distance of 2.4 H to the lee (415.8 g), although not significantly higher than average tuber$^{\text{mass}}$ at 1.7 H to the lee. Tuber$^{\text{mass}}$ was significantly lowest ($p < 0.05$) at 1.0 H to the lee(254.8 g).

Figure 2.1.7 illustrates the averaged variation of the potato above-ground$^{\text{mass}}$, in relation to the ViS1 windbreak. Above-ground$^{\text{mass}}$ was significantly highest ($p < 0.05$) at 2.4 H (31.2 g), and significantly lowest ($p < 0.05$) at 11.1 H (11.9 g) to the lee.

North stem length was significantly longest ($p < 0.05$) from 1.0 H to the windward side to 2.4 H on the leeward side (14.3 to 15.4 cm), and significantly shortest ($p < 0.05$) at 11.1 and 13.7 H to the lee (11.1 to 10.5 cm).

South stem length was significantly longest ($p < 0.05$) at 1.0 H to the windward side (16.7 cm). South stem length was significantly shortest ($p < 0.05$) at 13.7 H to the lee (13.2 cm), compared to all other treatments except for that at 11.1 H to the lee.

The ratio of south stem length over north stem length (north : south stem ratio) was significantly higher at 13.7 H to the lee (averaging 1.306) compared to all other treatments. This phenomenon indicated a significant preference for leaf and stem production on the southern side of each plant (relative to the plants' northern side) at 13.7 H to the lee. Plates A1.3 and A1.4 in Section $6^{\text{Ch. 3}}$ illustrate the visual difference in levels of crop morphology for the sheltered zone (at 2.0 H to the lee) and the unsheltered zone (at 13.7 H to the lee) respectively.

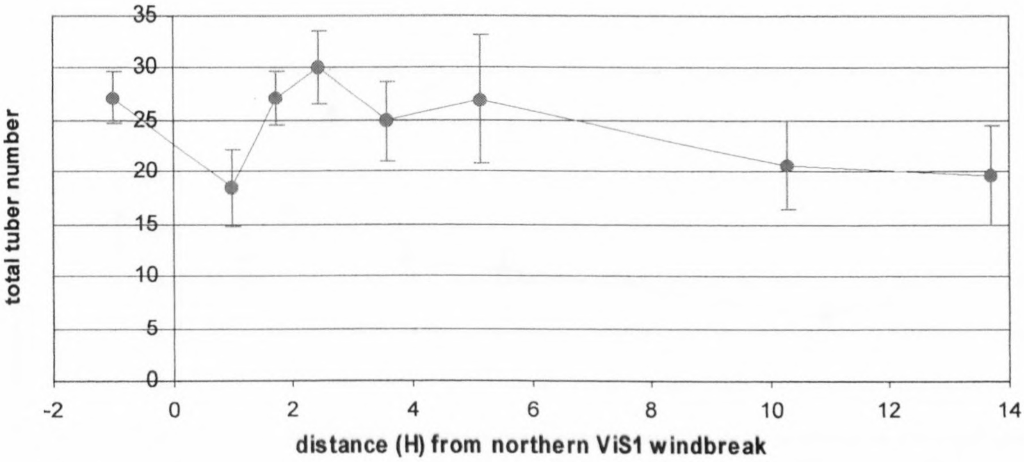

Figure 2.1.5 Averaged variation of the total tuber number, in relation to the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. Error bars indicate the level of the 95% confidence interval for each treatment. Data points have been joined to enhance visual presentation.

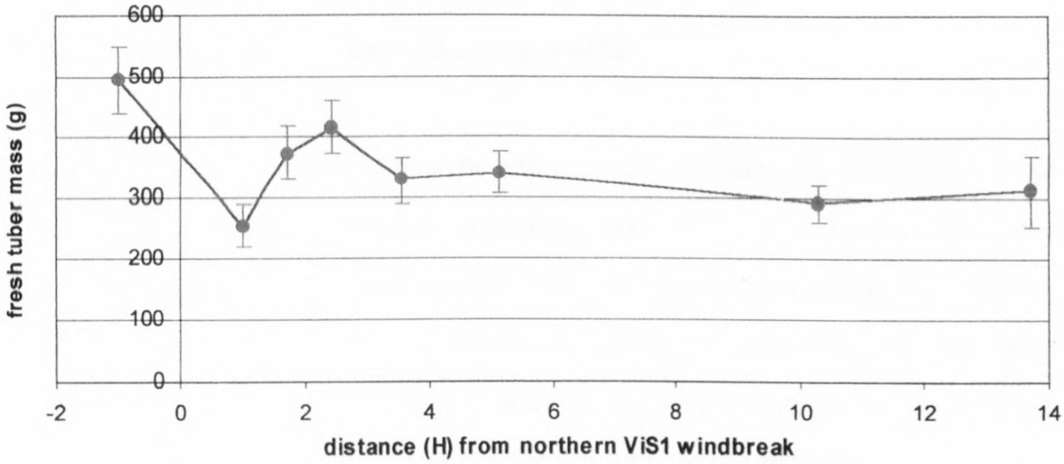

Figure 2.1.6 Averaged variation of potato tuber $^{\text{mass}}$, in relation to the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. Error bars indicate the level of the 95% confidence interval for each treatment. Data points have been joined to enhance visual presentation.

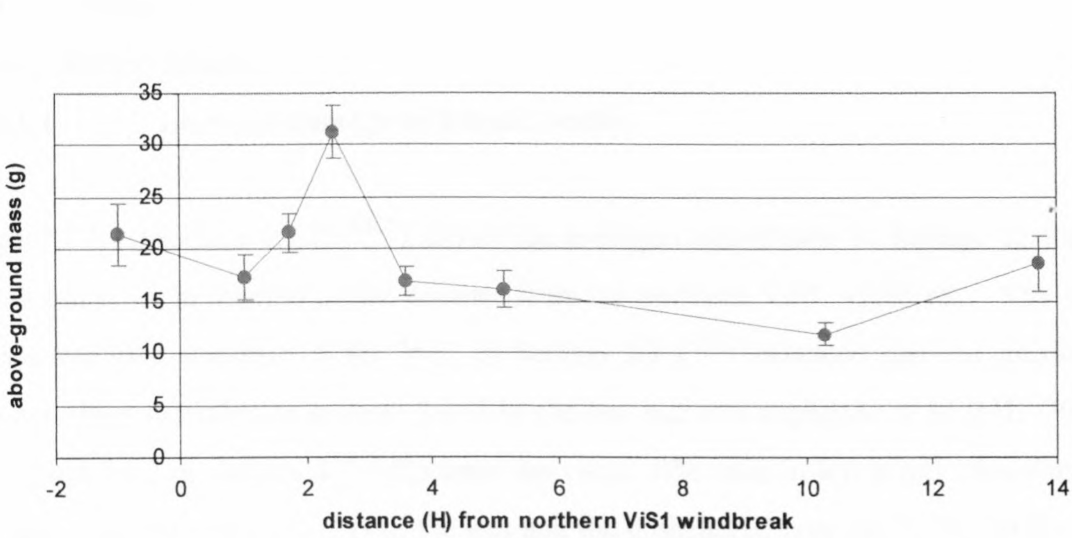

Figure 2.1.7 Averaged variation of potato above-ground$^{\text{mass}}$, in relation to the northern *P. radiata* windbreak at ViS1. Effective tree height (H) was 7.0 m. Error bars indicate the level of the 95% confidence interval for each treatment. Data points have been joined to enhance visual presentation.

1.2.5 Soil analysis in relation to the crop yields

The acidity of the soil suggested that the site was not commercially suitable for barley and potato cultivation (Prof. Andre Agenbag and Mr. Jan Lambrechts, personal communication), and this was indicated by the poor final yields described in Section 1.2.3 and 1.2.4$^{\text{Ch. 3}}$. P levels did not appear to be limiting, despite being slightly below the threshold level at 1.0 H to the windward side. As the yields recorded at this location were some of the highest for the site, P levels were not regarded as limiting.

The Ca : Mg ratio was below the optimum level at 1.0 and 5.1 H to the lee, potentially interacting with the poor final yields at these locations. However, the Ca:Mg ratio was similarly low at 1.0 H to the windward side, where a high yield occurred. Therefore the Ca:Mg ratio was not considered to be highly influential in the yields at 1.0 and 5.1 H to the lee. Consistent applications of N-fertiliser, as well as the subsequent absence of N-deficiency symptoms in each crop strip, indicated that N was not limiting.

1.3 Discussion

1.3.1 Barley damage

1.3.1.1 Leeward damage to 2-week barley

Figure 2.1.1 (Section 1.2.2.1 $^{\text{Ch. 3}}$) shows the averaged distribution of damage to the 2-week old crop, in relation to the distance from the northern ViS1 windbreak. The wind speed variation summarised for ViS1 in Section 3.1.1 $^{\text{Ch. 2}}$ indicated that the maximum shelter effect extended to at least 3.0 H to the lee, but was negligible at 11.0 H. Plates A1.1 and A1.2 in Section 6 $^{\text{Ch. 3}}$ illustrate the visual difference in levels of barley damage for the sheltered zone (at 2.0 H to the lee) and the unsheltered zone (at 13.7 H to the lee) respectively.

Damage was absent from 1.0 to 5.1 H. This indicated that maximum shelter extended to 5.1 H to the lee. The fully exposed leeward zone occurred at 13.7 H, where damage levels were significantly high ($X < 0.05$) by an average of 25%. An intermediate shelter effect was indicated at 7.3 and 11.1 H, where an average of 7 and 9% of the crop was damaged respectively.

1.3.1.2 Leeward damage to 6-week barley

Figure 2.1.2 in Section 1.2.2.2 $^{\text{Ch. 3}}$ illustrates the averaged distribution of damage to the 6-week old crop, in relation to the distance from the northern ViS1 windbreak. Class-2 damage (denoting severe damage, whereby the barley stems were levelled onto the ground) was absent from 1.0 to 7.3 H and significantly prevalent ($X < 0.05$) from 11.1 to 13.7 H (averaging 35 to 98%). This indicated that maximum shelter extended to 7.3 H, and intermediate shelter extended to approximately 11.1 H. Although minor damage (Class-1 damage denoting that lower leaves were pushed onto the ground) increasingly occurred from 3.6 to 7.3 H, this level of damage was not considered to significantly affect the crop. However, it did indicate a progressive erosion of the extent of shelter.

1.3.1.3 Summary of barley damage

From both damage assessments described in Section 1.3.1.1 and 1.3.1.2 $^{\text{Ch. 3}}$, the extent of maximum leeward shelter was indicated to extend to 7.3 H, with intermediate shelter extending to 11.1 H. The fully exposed zone occurred at 13.7 H, where significant damage ($X < 0.05$) occurred. Rainfall was plentiful and thus water could not have been limiting.

Soil variations could not have influenced the crop damage that was assessed, therefore wind speed variation across the site remained completely responsible for the variation of crop damage. The nature of the crop damage also indicated that wind was the main factor. All damaged plants had fallen and remained in the same direction as that of the north-westerly winds. A combination of strong winds and rain resulted in the fallen plants being plastered onto the soil surface. Severe wind may lead to the burial of newly emerged crops, pull young seedlings from the soil, or partially expose their roots (Woodruff *et al.*, 1972). Increased wind speeds might cause soil particles to be mobilised by the shearing force of the wind on the soil surface, and these blowing particles will abrade and damage seedlings.

1.3.2 Leeward barley crop

1.3.2.1 Barley head number

As a result of the zone of maximum shelter to the leeward side, barley head numbers were significantly higher ($p < 0.05$) at 1.7 and 2.4 H than at distances beyond 7.3 H (Table 2.1.2 and Figure 2.1.3 in Section 1.2.3 $^{\text{Ch. 3}}$). Average grain head number decreased roughly linearly from 2.4 to 13.7 H (27 to 3 heads respectively). Given that the soils at 1.7 and 13.7 H were similar (indicated in the Munsell colour codes and the soil analysis described in Section 1.2.1 $^{\text{Ch. 3}}$), then the absence of the shelter effect at 13.7 H resulted in a significantly reduced ($p < 0.05$) head production (by an average of 88%), relative to 2.4 H.

The rapid reduction of yield from 2.4 to 3.6 H was due to a poor soil occurring at 3.6 H (Table 2.1.1 in Section 1.2.1$^{\text{Ch. 3}}$). The lower yields at 3.6 H (compared to 2.4 H) could not be attributed to wind, as this location was in the zone of maximum shelter. This was evidenced from the barley damage assessments summarised in Section 1.3.1.3$^{\text{Ch. 3}}$ and the reduced wind speeds recorded at 3.0 H in Section 1.3.1.2$^{\text{Ch. 2}}$.

1.3.2.2 Proportion of total head$^{\text{mass}}$ from above-ground$^{\text{mass}}$

A similar trend to that described for barley head number also occurred for the transformed proportions of head$^{\text{mass}}$ from total$^{\text{mass}}$, where proportions were significantly higher ($p < 0.05$) from 1.7 to 3.6 H, compared to 13.7 H (Table 2.1.2 and Figure 2.1.4 in Section 1.2.3$^{\text{Ch. 3}}$)

The transformed proportion of total head$^{\text{mass}}$ from above-ground$^{\text{mass}}$ showed a decrease from 2.4 to 13.7 H. Given that the soils at 2.4 and 13.7 H were similar (indicated in the Munsell colour codes and the soil analysis described in Section 1.2.1$^{\text{Ch. 3}}$), the absence of the shelter effect at 13.7 H significantly reduced ($p < 0.05$) the transformed proportion of total head$^{\text{mass}}$ from above-ground$^{\text{mass}}$ (by an average of 63%) relative to 2.4 H.

Compared to the trend for head number, the shelter effect was more clearly defined and its extent was possibly more accurately represented by the trend recorded for the proportion of head$^{\text{mass}}$ from total$^{\text{mass}}$. This was possibly an indication the proportion was less sensitive to soil variation. Therefore, the trend was likely to be more closely related to wind speed variation in relation to the distance from the windbreak. Physical damage to crops at the seedling stage might delay grain filling (Woodruff *et al.,* 1972).

1.3.2.3 Other leeward trends for barley

A summary of the relevant data is shown in Table 2.1.2 (Section 1.2.3$^{\text{Ch. 3}}$). Despite not being significant ($p > 0.05$), total head$^{\text{mass}}$, above-ground$^{\text{mass}}$, and leaf and stem$^{\text{mass}}$ showed similar trends to that described in Section 1.3.2.1 and 1.3.2.2$^{\text{Ch. 3}}$. In most cases, yields were higher at 11.1 and 13.7 H, compared to those at 7.3 H. This was attributed to the more fertile soil that occurred beyond 7.3 H to the lee. As indicated by the Munsell colour codes in Table 2.1.1 (Section 1.2.1$^{Ch. 3}$), the soil at 11.1 to 13.7 H was comparable to the soils from 1.0 to 2.4 H to the lee. Yields were higher at 1.0, 1.7, and 2.4 H compared to those at 11.1 and 13.7 H. A shelter effect was the most likely result of the increased yields from 1.0 to 2.4 H, compared to the unsheltered zone extending from 11.1 H. Therefore, the absence of the shelter effect at 13.7 H resulted in a reduced ($p > 0.05$) total head^{mass}, above-ground^{mass}, and leaf and stem^{mass} (by an average of 87, 42, and 31% respectively), compared to that at 2.4 H.

The trend for average head^{mass} was the only exception to this general trend. Regardless, the absence of the shelter effect at 13.7 H resulted in a reduced ($p > 0.05$), transformed proportion of total head^{mass} from above-ground^{mass} (by an average of 16%), compared to that at 2.4 H.

The soil at 13.7 H was the most fertile at the site (Dr. Freddie Ellis, personal communication). The increase of yields at 13.7 H for above-ground^{mass} and leaf and stem^{mass} (compared to those at 11.1 H) suggested that vegetative production was influenced more by soil fertility than by wind speed. However, the reduced yields at 13.7 H (compared to 11.1 H) for total head^{mass}, average head^{mass}, proportion of head^{mass} from total^{mass}, and grain head number suggests that grain production (or grain initiation) was influenced by wind speed more than any soil effect. This is further implied by the greater yield response resulting from the shelter effect from grain related data, compared to non-grain related data. The rate of tillering in grasses was significantly reduced at high wind speeds (Russell and Grace, 1978b).

1.3.2.4 Extent of leeward shelter for barley

The trends described from Section 1.3.2.1 to 1.3.2.3$^{Ch. 3}$ suggested that a maximum crop shelter effect extended up to 7.3 H to the leeward side of the ViS1 windbreak. Distances beyond this zone were regarded as being fully exposed.

1.3.3 Leeward potato crop

1.3.3.1 Potato tuber number

Total tuber number (and also small tuber number) was significantly highest ($p < 0.05$) from 1.7 to 5.1 H to the lee, compared to the total tuber numbers further leeward (Table 2.1.3 and Figure 2.1.5 in Section 1.2.4$^{\text{Ch. 3}}$). Given that the soils at 2.4 and 13.7 H were similar (indicated in the Munsell colour codes and the soil analysis described in Section 1.2.1$^{\text{Ch. 3}}$), the absence of the shelter effect at 13.7 H resulted in a significantly reduced ($p < 0.05$) total tuber number, and small tuber number, (by an average of 34 and 44% respectively), compared to 2.4 H. In contrast, the absence of the shelter effect at 13.7 H resulted in an insignificant reduction ($p > 0.05$) of large tuber number, relative to 2.4 H. This may indicate that an absence of a shelter effect caused the potato plants to invest resources into fewer but larger potatoes, due to inhibition of tuber initiation by the absence of a shelter effect.

1.3.3.2 Potato morphology

A summary of the relevant data is shown in Table 2.1.3 (Section 1.2.4$^{\text{Ch. 3}}$). At 13.7 H only, leeward potato morphology (south : north stem ratio) indicated a significantly higher stem length ($p < 0.05$) on the southern side of each potato plant, compared to the respective northern sides of each potato plant. This may have been due to disproportionate tissue damage to the windward section of each plant, or disproportionate tissue growth on the leeward section of each plant. A combination of these two reponses was likely. The absence of the shelter effect at 13.7 H resulted in a significantly increased ($p < 0.05$) south:north stem ratio, compared to 2.4 H (by an average of 22%).

Plates A1.3 and A1.4 in Section 6$^{\text{Ch. 3}}$ illustrate the typical morphology of a potato plant in the sheltered zone (at 2.0 H to the lee) and in the unsheltered zone (at 13.7 H to the lee) respectively. Note the lack of symmetry in the latter illustration.

Plants became more streamlined as wind speeds increase to reduce wind resistance (Cleugh, 1998). Certainly, damage to tissue on the northern side was evident on many of the potato plants growing at 13.7 H to the lee, and subsequently responded by favouring growth where damage was least prevalent. No soil effect could be considered to interact with this variable, because such an index acted as a standardisation of all growing conditions except for the influence of wind. Therefore, the index may have been more highly correlated with a shelter effect than other variables used previously that were more vulnerable to additional interactions.

Stem length, for both north and south sides of the plants, was significantly higher ($p < 0.05$) in the zone from 1.0 H to the windward side to 3.6 H to the lee, compared to 11.1 and 13.7 H to the lee. As the soils at 2.4 and 13.7 H were similar, the absence of the shelter effect at 13.7 H resulted in a significantly reduced ($p < 0.05$) north stem length (by an average of 32%) and a significantly reduced ($p < 0.05$) south stem length (by an average of 14%), compared to 2.4 H. Therefore, winds reduced stem length on both sides of each plant, but affected the north side more than the south side. Note that a significant interaction between distance and replicates also occurred for the north-stem length data.

1.3.3.3 Potato tuber ^{mass}

Potato tuber ^{mass} was significantly highest ($p < 0.05$) at 2.4 H (Table 2.1.3 and Figure 2.1.6 in Section 1.2.4$^{Ch. 3}$). Given that the soils at 2.4 and 13.7 H were similar (indicated in the Munsell colour codes and the soil analysis described in Section 1.2.1$^{Ch. 3}$), the absence of the shelter effect at 13.7 H resulted in a significantly reduced ($p < 0.05$) potato tuber ^{mass} (by an average of 25%), relative to 2.4 H.

1.3.3.4 Potato above-ground ^{mass}

Leeward potato above-ground ^{mass} was significantly highest ($p < 0.05$) at 2.4 H (Table 2.1.3 and Figure 2.1.7 in Section 1.2.4$^{Ch. 3}$). Given that the soils at 2.4 and 13.7 H were similar (indicated in the Munsell colour codes and the soil analysis described in Section

1.2.1 $^{\text{Ch. 3}}$), the absence of the shelter effect at 13.7 H resulted in a significantly reduced ($p < 0.05$) potato above-ground$^{\text{mass}}$ (by an average of 40%), relative to 2.4 H.

1.3.3.5 Extent of leeward shelter for potatoes

Rapid yield decreases from 5.1 to 11.1 H to the lee suggested that the extent of shelter for potatoes ended within this zone. The south : north stem ratio begins to increase at 11.1 H, but significantly increased ($p < 0.05$) only at 13.7 H. This suggests that the influence of the shelter effect extended as far as 11.1 H, although the extent of maximum shelter extended to the zone between 5.1 to 11.1 H. The loss of the potato crop at 7.3 H due to excessive soil moisture was therefore very unfortunate, because the survival of the crop at this location would have provided more detailed information concerning the extent of the shelter effect for the leeward potato crop. The approximate zone of maximum leeward shelter possibly extended to 8.0 H, followed by a zone of rapidly decreasing shelter from 8.0 to 11.1 H to the lee. Distances beyond this zone were considered fully exposed.

1.3.4 Extent of the leeward effect, on both crop species

The summarised estimations of the extent of leeward shelter for the barley damage assessments (Section 1.3.1.3 $^{\text{Ch. 3}}$), the barley crop yield assessments (Section 1.3.2.4 $^{\text{Ch. 3}}$), and the potato crop yield assessments (Section 1.3.3.5 $^{\text{Ch. 3}}$) indicated that leeward shelter generally extended to 7.3 H to the leeward side of the ViS1 windbreak, followed by a zone of rapidly decreasing shelter to approximately 11.1 H. The zone beyond this distance was regarded as fully exposed. The shelter effect was clouded by soil interactions, but was evident nonetheless. This estimate of the shelter extent was consistent with the wind speed summary for ViS1 (Section 3.1.1 $^{\text{Ch. 2}}$), which indicated that shelter extended to at least 3.0 H to the lee, but was absent at 11.0 H.

Other investigations reported that maximum wind speed reductions occurred in the zone ranging from 3.0 to 6.0 H (Cleugh and Hughes, 2000; Cleugh, 1998; Sun and Dickinson, 1997; Hodges and Brandle, 1996; Bird, 1988, Ujah and Adeoye, 1984). The area of maximum shelter was estimated by Nuberg (1998) to range from 4.0 and 12.0 H. From wind tunnel tests, Tibke (1988) reported that maximum shelter extended to 9.0 H.

Intermediate shelter has been estimated to extend to approximately 10.0 H (Cleugh, 1998; Hodges and Brandle; 1996, Pretzechel *et al.*, 1991; and Dickey, 1988). There are other estimates of the intermediate shelter effect extended to 12.0 H (Bird, 1988), 16 H (Banzhaf *et al.*, 1992; Ujah and Adeoye; 1984), and as far as 20.0 H (Haigh, 1994; Sun and Dickinson, 1994; Rocheleau *et al.*, 1988) and 30.0 H (Cleugh and Hughes, 2000; Marshall, 1967).

Given that the soils at 2.4 and 13.7 H were similar (indicated in the Munsell colour codes and the soil analysis described in Section 1.2.1$^{\text{Ch. 3}}$), the absence of the shelter effect at 13.7 H resulted in significant reductions ($p < 0.05$) of barley grain head number (by an average of 88%), transformed barley head$^{\text{mass}}$ from the total$^{\text{mass}}$ (63%), potato tuber$^{\text{mass}}$ (25%), potato above-ground$^{\text{mass}}$ (40%), total potato tuber number (34%), small potato tuber number (44%), and south : north potato stem length (22%) relative to 2.4 H.

On fruit farms in the Western Cape Region, windbreaks were spaced at a distance of 12.0 to 14.0 H with the objective of decreasing the average wind speed throughout the orchard by at least 30% (Myburgh and Viljoen, 1979). From the results at ViS1, such a consistently high level of shelter cannot be considered to be possible for severe wind speeds. A recent trend for closer spacing of windbreak networks throughout the orchard regions of the Western Cape Region may be an indication of a growing level of caution by farmers for prevailing winds. It may also be an indication of a growing level of respect by farmers for the benefits of windbreaks on their crops.

Wound responses and production of non-productive recovery tissue (a process known as thigmomorphogenesis) will be at the expense of productive tissues (Grace and Russell, 1982). Grace (1988) and Biddington (1985) also reported that wind stress affected plant morphology, resulting in smaller and more compact plants with a higher root-shoot ratio than non-stressed plants. Subsequently, crops that maintain a ratio of yield to their total biomass will produce reduced absolute yields because of their small size (Cleugh *et al.*, 1998).

When the microclimate is characterised by constant wind directions during the growing season, plants growing downwind of a windbreak will be consistently sheltered and protected from damage, leading to larger yields. As plants are able to recover from abrasion damage, continuous protection from all (not just strong) winds is required to produce a yield benefit (Cleugh *et al.*, 1998). The significant shelter effect at ViS1 therefore confirmed a near continuous shelter effect

1.3.5 Windward crop growth

The crop strip located at 1.0 H to the windward side of the windbreak provided misleading yield results. Although initially considered exposed to windward winds, the sheltering effect from the fynbos growing immediately windward of the crops (and also a possible fertility effect) allowed yields to be as high as those in the sheltered zone on the leeward side. This fynbos shelter effect at crop level was not indicated by the windward wind speed data in Section 1.3.1.2 $^{\text{Ch. 2}}$ because the anemometer unit was positioned at 1.5 m above ground level, thereby beyond the influence of the fynbos.

From both barley damage assessments in Section 1.3.1.1 and 1.3.1.2 $^{\text{Ch. 3}}$, the low amounts of damage recorded at 1.0 H to the windward side suggested that the shelter effect (at ground level) was at least intermediate in this zone. However, the significantly high yields ($p < 0.05$) recorded at 1.0 H to the windward side for grain head number, proportion of head $^{\text{mass}}$ from above-ground $^{\text{mass}}$ (Table 2.1.2 of Section 1.2.1 $^{\text{Ch. 3}}$), total tuber $^{\text{mass}}$ and large tuber number (Table 2.1.3 of Section 1.2.4 $^{\text{Ch. 3}}$) suggested that conditions for crop growth were optimal. Without the sheltering effect from the northerly fynbos and a likely fertility effect, yields may not have been so high at this windward location.

Despite the generally high potato yield at 1.0 H to the windward side compared to other distances, the number of small tubers (< 4 cm diameter) at 1.0 H to the windward side was significantly lower than the numbers recorded from 1.7 to 5.1 H to the lee. This was possibly the result of the potato (and barley) plants at this windward location potentially growing in the most ideal location at the site, due to low wind speeds, well structured and fertile soil (although the soil analysis in Section 1.2.1 $^{\mathrm{Ch.\ 3}}$ suggested slightly limiting P, and Ca : Mg levels), and high levels of radiation. Subsequently these potatoes developed their tubers at a much faster rate relative to other locations at the site. This may explain why the proportion of larger potatoes was higher at 1.0 H to the windward side than for any other location. It also suggests that total tuber numbers provided a more complete insight into the response of tuber growth compared to separate components of small or large tuber numbers.

1.3.6 Negative effects of the windbreak on both crops at ViS1

1.3.6.1 Extent of the negative effect

Crop yields at 1.0 and 1.7 H could be directly compared with each other as the soils were similar, as indicated in the Munsell colour codes and the soil analysis described in Section 1.2.1 $^{\mathrm{Ch.\ 3}}$. A summary of barley data is shown in Table 2.1.2 (Section 1.2.3) and a summary of the potato data is shown in Table 2.1.3 (Section 1.2.4 $^{\mathrm{Ch.\ 3}}$). Compared to the leeward yields at 1.7 H, those at 1.0 H were significantly reduced ($p < 0.05$) for barley head number (by an average of 61%), transformed proportion of barley head $^{\mathrm{mass}}$ from above-ground $^{\mathrm{mass}}$ (56%), potato tuber $^{\mathrm{mass}}$ (32%), total potato tuber number (32%), and small potato tuber number (33%).

Both locations experienced similarly low wind speeds, as described in the fourth last paragraph of Section 1.3.1.3 $^{\mathrm{Ch.\ 2}}$. Similar wind speeds and similar soils at 1.0 and 1.7 H therefore suggested that the significantly lower yields at 1.0 H were attributed to shading by the adjoining northern windbreak. However, rapid recovery of yields beyond this distance indicated that the competitive effect was highly restricted. From the soil analysis data, the slightly limiting Ca : Mg ratio at 1.0 H to the lee cannot be regarded as a significant influence on the crop growth at this distance, as it is just below the optimum range (Prof. Andre Agenbag and Mr. Jan Lambrechts, personal communication).

Worldwide research indicates that windbreaks generally caused a reduction in crop growth up to 1.5 to 2.0 H from the trees (Kowalchuk and De Jong, 1995; Puri *et al.*, 1992; Baldwin, 1988; Lyles *et al.*, 1984). Cleugh (1998) concluded that past evidence indicated maximum yield gains were typically found in the leeward sheltered zone between 3.0 and 10.0 H. Eicker *et al.* (1986), investigating apple orchard yields in the Western Cape of South Africa, reported yield reductions from 2.0 to 4.0 H from *P. radiata* windbreaks. Sun and Dickinson (1994) reported a below average potato yield occurring in a far greater zone of up to 5.0 H.

1.3.6.2 Magnitude of the net competition effect

Crop yields at 1.0 and 13.7 H could be directly compared with each other as the soils were similar, as indicated by the Munsell colour codes and the soil analysis described in Section 1.2.1 $^{\text{Ch. 3}}$. As described in the fourth last paragraph of Section 1.3.1.3 $^{\text{Ch. 2}}$, wind speeds at 1.0 H were notably lower compared to wind speeds at beyond 11.0 H. The similar soils at 1.0 and 13.7 H therefore suggested that differences in yields at these two locations were attributed to either differences in levels of wind speed or differences in levels of shading. A summary of the barley and potato data is shown in Table 1.1.2 (Section 1.2.3 $^{\text{Ch. 3}}$) and Table 1.2.4 (1.2.4 $^{\text{Ch. 3}}$) respectively. In all cases described below, crop yields were not significantly different ($p > 0.05$).

For the barley crop, yields at 13.7 H were lower compared to the yields at 1.0 H. This indicated that crop yields were reduced more by the effect of unsheltered wind speeds than by the effect from competition. Compared to 1.0 H, yield reductions occurred at 13.7 H for the barley head number, and the transformed proportion of barley head $^{\text{mass}}$ from above-ground $^{\text{mass}}$ (by an average of 67 and 9% respectively). Figures 2.1.3 to 2.1.4 in Section 1.2.3 $^{\text{Ch. 3}}$ illustrate these respective differences .

Conversely for the potato crop, yields at 13.7 H were generally higher compared to the yields at 1.0 H. This indicated that crop yields were reduced more by the effect from competition than by the effect of unsheltered wind speeds. Compared to 1.0 H, average yield reductions occurred at 13.7 H for the potato tuber $^{\text{mass}}$ (19%), and the total potato tuber number (7%). Figures 2.5 to 2.6 in Section 1.2.4 $^{\text{Ch. 3}}$ illustrate these respective differences.

For the small potato tuber number, average yields at 13.7 H were lower (by 12%) compared to the yields at 1.0 H. However, for the large potato tuber number, average yields at 13.7 H were higher (by 44%) compared to the yields at 1.0 H. As described earlier in Section 1.3.3.1 $^{\text{Ch. 3}}$, this suggested that an absence of a shelter effect caused inhibition of tuber initiation. Therefore, resources were devoted to fewer but larger potatoes.

Limited competition may be a small price to pay for a greatly increased resource capture and overall system productivity (Howard *et al.*, 1997). Average worldwide percentage yield increases in crop production of 5 to 25% are common (Brandle *et al.*, 1992) and there is potential of 50% or more (Baldwin, 1988; Rocheleau *et al.*, 1988). All estimates take into consideration the loss of output from land taken out of production by the windbreaks.

From investigations of windbreaks in the USA, yield increases in cereal crops ranged from 5% on "good land" to 18% on "poor land" (Haigh, 1994). Experiments conducted over 25 years in the Steppe region of the Ukraine indicated a 22% increase compared to unsheltered fields (Miloserdov and Semyakin, 1984). Sun and Dickinson (1997, 1994) reported a 6.7 and 7.7% increase in potato yield respectively, and Puri *et al.* (1992) found a 4 to 10% cotton yield increase; despite all of these experiments having low yields near the windbreaks. Kort (1988) reported a 50% yield reduction of spring wheat from up to 1.0 H, but also a windbreak induced increase from 1.0 to 15.0 H. Kort (1988) concluded that there was a 3.5% net increase in yield.

Wheat and mustard increased linearly with increasing distance from a row of *E. tereticornis* windbreaks in semi-arid India. Trees used five times more water compared to the mustard crop, and thereby were deemed unsuitable as windbreaks adjacent to field crops in deep water table conditions of arid and semi-arid conditions (Malik and Sharma, 1990). *Acacia nilotica* windbreaks reduced wheat yield up to 8.5 m distance on the leeward side. The average yield was 58% lower at 1.0 m and 22% lower at 8.5 m. Beyond that, there was no significant competitive effect on wheat production. The yield was not significantly higher than the control yield, but this was probably due to problems with experimental design (Khan and Ehrenreich, 1994). In sub-humid temperate New Zealand, low crop yields were located in the rain shadow where interception of precipitation by the tree crowns was highest (Yunasa *et al.*,1995).

1.3.6.3 Mechanism of the competition effect

Below-ground competition at the tree/crop interface was not considered to be high for two reasons. Firstly, no evidence of tree roots was observed during cultivation of the soil at 1.0 H on the windward and leeward sides of the windbreak. This suggested that tree roots (and therefore tree root competition) extended across a limited range (less than 1.0 H) for the 4-year old *P. radiata* windbreak at ViS1. Secondly, the soil moisture data from the weather station (summarised in Section 1.3.3 $^{\mathrm{Ch.\ 2}}$) indicated that moisture levels near the soil surface were actually higher at 1.0 H than at 3.0 and 11.0 H.

Therefore, the competition effect responsible for the reduced yield at 1.0 H to the lee was attributed to an interaction occurring above the ground. As mentioned in Section 1.3.3 $^{\mathrm{Ch.\ 2}}$, higher levels of radiation were intercepted by the windbreak at 1.0 H to the lee, compared to any other location. The crops growing at 1.0 H to the lee were located immediately south of the windbreak, hence many more hours of shading for each day occurred in this restricted zone. This became increasingly the case when the sun was lower during the winter months.

Shade from solar radiation directly affects plant growth because of the reduction of photosynthetically active radiation and indirectly because of its effects on soil and air temperatures and evaporation. From a highly simplified model, Abel *et al.* (1997) demonstrated that an east-west orientated windbreak at mid-latitudes shaded areas at times extended well beyond the sheltered zone in winter. Therefore, the orientation and height of the windbreak, in combination with the position of the sun relative to the windbreak, determines the direction and extension of the shade (Mayus *et al.*, 1999a).

Using the relationship between crop yields and microclimatic conditions within a network of windbreaks in temperate China, Song *et al.* (1987) analysed multivariate regression to provide an equation that predicted yield under various conditions. Factors increasing crop yield were reductions in wind speed and in air saturation deficit, and increases in soil moisture caused by a reduction of evaporation. Crop yield was reduced by a reduction in solar radiation caused by windbreak shading.

From a model predicting the effect of the tree species *Bauhinia refescens* on millet (*Pennisetum glaucum*) in Niger, Mayus *et al.* (1999b) found that the simulations showed a strong yield reduction up to 2.0 H from the windbreak due to shading. Maximum reduction (up to 35%) occurred directly adjacent the windbreak at 0.5 H.

However, windbreak shade may not be an important issue for rain fed cropping systems, because competition for light in water-limited environments is of minor importance compared to competition for water (Ong *et al.*, 1991b). The effect of water stress on crop yields is far more dominant than the effect of shading on crop yields. Therefore, the shade effect is evident only when water remains limited (Mayus *et al.*, 1999b). Provided that water was not limiting, millet yield was reduced proportionally to the degree of shading (Corlett *et al.*, 1992).

A combination of shade and wind speed reduction had a positive effect on water availability, with total evaporation being reduced up to 2.5 H from the windbreak (Mayus *et al.*, 1999a). The reduction of evaporation was most intense at the first crop row. As wind speed reduction remained constant up to 5.0 H, shading was considered the main factor causing the reduction of evaporation. Yields were reduced from 0.5 to 2.0 H from the windbreak because, within this zone, competition out-weighed the beneficial effects of lower evaporation.

1.4 Conclusions of microclimate variation at ViS1

1.4.1 Barley damage

The 2-week damage assessment indicated that damage was absent from 1.0 H to 5.1 H, intermediate at 7.3 and 11.1 H (an average of 7 and 9% of the barley damaged respectively), and significantly highest ($X < 0.05$) at 13.7 H (by an average 25% respectively). The 6-week damage assessment indicated the severe damage was absent from 1.0 to 7.3 H and significantly prevalent ($X < 0.05$) from 11.1 to 13.7 H (by an average 35 to 98%).

From both damage assessments the extent of maximum leeward shelter was indicated to extend to 7.3 H, with intermediate shelter extending to 11.1 H. The data from the damage assessments had little potential to interact with soil variations, and subsequently variation of crop damage was solely attributed to the shelter effect.

1.4.2 Barley yields

Barley and potato yields generally showed a decrease from 2.4 to 13.7 H. As the soils at 1.7 and 13.7 H were similar, direct comparisons of yield were made to assess the shelter effect. Compared to 2.4 H, the absence of the shelter effect at 13.7 H resulted in a significantly reduced ($p < 0.05$) head number and transformed proportion of total head ^{mass} from above-ground ^{mass} (by an average of 88 and 63%).

Despite not being significant ($p > 0.05$), total head ^{mass}, above-ground ^{mass}, and leaf and stem ^{mass} showed similar trends. Compared to 11.1 H, the increase of yields at 13.7 H for above-ground ^{mass} and leaf and stem ^{mass} suggested that vegetative production was influenced more by soil fertility than by wind speed. Compared to 11.1 H, the reduced yields at 13.7 H for total head ^{mass}, average head ^{mass}, proportion of head ^{mass} from total ^{mass}, and grain head number suggests that grain production (or grain initiation) was influenced by wind speed more than any soil effect.

1.4.3 Potato yields

Compared to 2.4 H, the absence of the shelter effect at 13.7 H resulted in a significantly reduced ($p < 0.05$) potato tuber ^{mass} (by an average of 25%), potato above-ground ^{mass} (40%) total tuber number of (34%), and a reduced small tuber number (44%). In contrast, the absence of the shelter effect at 13.7 H resulted in an insignificantly reduced ($p > 0.05$) large tuber number, relative to 2.4 H. This might indicate that an absence of a shelter effect caused potato plants to invest resources for fewer but larger potatoes, due to inhibition of tuber initiation by the absence of a shelter effect.

At 13.7 H only, leeward potato morphology (south : north stem ratio) indicated a significantly higher stem length ($p < 0.05$) on the southern side of each potato plant, compared to the respective northern sides of each potato plant. This may have been due to disproportionate tissue damage to the windward section of each plant, or disproportionate tissue growth on the leeward section of each plant. Importantly, these proportions excluded any soil interaction. Compared to 2.4 H, the absence of the shelter effect at 13.7 H resulted in a significantly increased ($p < 0.05$) average south : north stem ratio (by an average 22%), and a significantly reduced ($p < 0.05$) north stem length of by an average 32% and south stem length of by an average 14% relative to 2.4 H. Therefore, winds reduced stem length on both sides of each plant, but affected the north side more than the south side.

1.4.4 Extent of shelter

For both crops, leeward shelter generally extended to 7.3 H to the leeward side of the ViS1 windbreak, followed by a zone of rapidly decreasing shelter to approximately

11.1 H. The zone beyond this distance was regarded as fully exposed. The shelter effect was clouded by soil interactions, but was evident none the less.

The crop strip located at 1.0 H to the windward side of the windbreak provided misleading yield results. Although initially considered exposed to windward winds, the sheltering effect from the fynbos growing immediately windward of the crops allowed yields to be as high as those in the sheltered zone on the leeward side. A soil fertility effect was also probable at this windward location.

1.4.5 Competition effect

Similar wind speeds and similar soils at 1.0 and 1.7 H suggested that significantly lower yields at 1.0 H were attributed to shading by the adjoining northern windbreak. Crop yields at 1.0 and 1.7 H could be directly compared with each other as the soils were similar. Compared to the leeward yields at 1.7 H, those at 1.0 H were significantly reduced ($p < 0.05$) for barley head number (by an average 61%), transformed proportion of barley head$^{\text{mass}}$ from above-ground$^{\text{mass}}$ (56%), potato tuber$^{\text{mass}}$ (32%), total potato tuber number (32%), and small potato tuber number (33%). The rapid recovery of yields beyond this distance indicated that the competitive effect was highly restricted.

Barley yield differences between 1.0 and 13.7 H were not significantly different ($p > 0.05$), indicating that the effect of unsheltered wind speeds was similar to the effect from shading. Crop yields at 1.0 and 13.7 H could be directly compared, as the soils at these locations were similar. Potato yield differences between 1.0 and 13.7 H were also not significantly different ($p > 0.05$). An exception to this was for the large potato tuber number, which was significantly higher ($p < 0.05$) at 13.7 H, compared to 1.0 H. This suggested that large tuber production was reduced more by the effect from competition than by the effect of unsheltered wind speeds.

2 WOLSELEY SITE 3 (WoS3)

2.1 Method

2.1.1 Regional description

WoS3 was located 6 km south-west of Wolseley (longitude: 19°12′E, latitude: 33°26′S, altitude: 260 m) on the farm "Verrekyker" of Fanie and Elizabeth Redelinghuys. Plate 1.1 in Section 3.2 $^{\text{Ch. 1}}$ illustrates the location of WoS3 in the Western Cape Region.

Table 1.2.1 in Section 2.1.2 $^{\text{Ch. 2}}$ shows the summarised long term and 1999 data collected from the "La Plaisante" DWAF weather station located 4 km west of WoS3. The average daily maximum temperature in this region was 30.4°C for the hottest months (January and also February) and the average daily minimum temperature for the coolest month (July) was 6.6°C. The site is in a temperate winter rainfall region, with June having the highest average monthly rainfall (102.1 mm), and January having the lowest average monthly rainfall (11.9 mm). Data for total evaporation and Relative Humidity (RH) are also included in Table 1.2.1.

2.1.2 Site description

An aerial view of WoS3 is shown in Plate 2.2.1 and a profile view of the southern windbreak with adjoining crop strips is shown in Plate 1.3 in Section 3.2 $^{\text{Ch. 1}}$. This site had a *C. cunninghamiana* windbreak with an average effective height (H) of 5.0 m adjoining the north and south borders of a vacant block of land. Distance between the two windbreaks was 94.0 m (18.8 H). The windbreaks were orientated in a northeast-east to southwest-west direction, and gaps were minimal along the windbreak profile. Both of the 2-year old windbreaks were single rowed and the trees were spaced 1.0 m from each other. The width of the experimental site was 20.0 m.

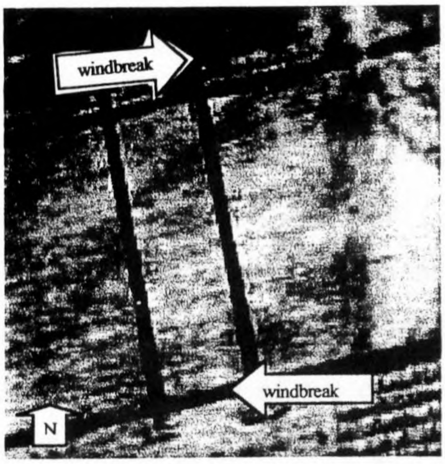

Plate 2.2.1 Aerial view of WoS3. Prevailing winds were south-easterly. Note the drainage line meandering between the northern and southern windbreaks.

Access tracks were not present along the windbreaks, and therefore the experimental design could be extended directly to each of the windbreaks. Each windbreak extended for approximately 1 km on either side of the site. Other crops and orchards existed on the other side of each of the windbreaks, thus preventing any measurements beyond the site boundary. The site had remained fallow for the last decade in anticipation of eventual orchard establishment between the two windbreaks in May 2001.

An initial soil investigation on 12 January 1999 provided an insight into the soil variation across the vacant block of land. This investigation involved a rapid collection of surface soil samples spaced at 30.0 m x 30.0 m from each other. The most homogenous 30.0 m x 94.0 m section between both windbreaks was thereby selected for the site. Soil pits were not excavated at this site as the Dundee 1210 soil classification (Munsell Color Co., 1975) described for another Wolseley site (WoS1) a year earlier was known to be consistent throughout this region (Dr. Freddie Ellis, personal communication). The site description of WoS1 (located 2 km east of WoS3) is shown in further detail in Section 4.1.2$^{\text{Ch. 3}}$. On 1 October 1999, three points located across the WoS3 site were drilled with an auger to a depth of 1.2 m to confirm this assumption. The soil profiles from the three soil pits at WoS1 indicated:

1. An orthic A horizon from 0 to 30 cm depth, about 10% clay content, and a fine to medium sand grade

2. A stratified alluvium material with signs of wetness (C1 and C2 horizon) from 30 to 120 cm depth, about 12% clay content, and a fine to medium sand grade
3. A stratified alluvium material with signs of wetness (C3 horizon) from 120 to > 140 cm depth, about 3% clay content, and a medium to coarse sand grade.

Soil was also sampled on 1 October 1999 to a depth of 10 to 20 cm, at 1.5, 3.0, 5.0, 7.0, 9.0, 11.0, 13.0 and 15.0 H to the lee of the northern windbreak. Each collected sample was a composition of soil collected from three points at a specific distance from the southern windbreak. These points were located in the central region of the site, and 10.0 m apart from each other. Each composite sample was sealed in a labelled paper bag, and then air-dried for seven days. The dried soil was then analysed for the content of available-N, exchangeable cations (Na+, Ca++, P++, K+), and pH. Munsell colour-code descriptions were made for each soil sample (in both the wet and dry state) to provide further information concerning soil homogeneity across the site.

2.1.3 Experimental design

Plate 2.2.2 illustrates the experimental crop design for WoS3. The general shape of the design was a 25.0 m wide block extending 94.0 m between the two windbreaks. To minimise the area of the experiment, 25.0 m long strips (each at a width of 3 m) were designated at specific distances parallel to the windbreak. Strips were designated at 3.0 to 5.0, 8.0 to 10.0, 13.0 to 15.0, 23.0 to 25.0, 33.0 to 35.0, 44.5 to 46.5, 53.0 to 55.0, 63.0 to 65.0, 73.0 to 75.0, 83.0 to 85.0, and 89.0 to 91.0 m (1.0, 2.0, 3.0, 5.0, 7.0, 9.0, 11.0, 13.0, 15.0, 17.0 and 18.0 H respectively) to the lee of the southern windbreak. Areas between these strips remained fallow and were excluded from the experimental design. Wind sensitive fodder barley (*Hordeum vulgare*) was sown within each strip. The 10 replicates were set perpendicular to the southern windbreak, so that each replicate was 2.0 m wide and intersected each crop strip.

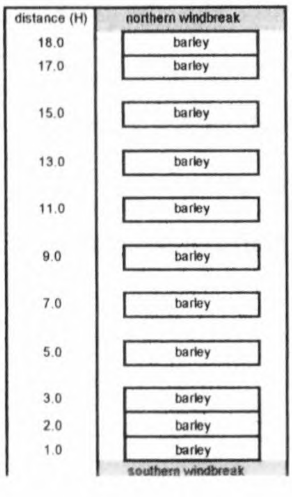

Plate 2.2.2 Experimental crop design for WoS3.

A buffer of 2.5 m was allocated on the east and west ends of each crop strip. The 10 replicates were arranged within the inner 20.0 m of each crop strip.

On 25 and 26 October 1999, the mature barley plots were cut at 5 cm height, and placed in labelled paper bags. From 27 to 29 October 1999, each collected sample was processed by a threshing machine that separated the leaf and stem$^{\text{mass}}$ from the grain$^{\text{mass}}$. Each processed component from each plot was sealed in a paper bag, oven dried for 24 hours at 80°C, and then weighed. The proportion of grain$^{\text{mass}}$ from total$^{\text{mass}}$ was also calculated. From each of the grain samples, 100 grains were randomly selected and weighed. Random selection was achieved by pouring the grain of each sample onto a surface, and then halving the sample. A further half was randomly selected, mixed, and divided by half again. The process continued until about 500 grains remained, from which 100 grains were randomly selected. Thus, sub-sample$^{\text{mass}}$ of 100 grains was calculated for each sample.

2.1.4 Site preparation

The 11 designated crop strips were sprayed with 2 L / ha Roundup herbicide (glyphosate as the active ingredient, making up 360 g / L of the herbicide) on 25 May 1999, followed by ploughing of the strips by a tractor on 8 June 1999. On the same day, fertilizer (400 kg / ha super-phosphate (10.5% P), 100 kg / ha 2:3:2 (22), and 100 kg / ha LAN (28% N)) and fodder barley (80 kg / ha) was evenly applied by hand to each cultivated strip. Fertilizer and seed were immediately ploughed into the soil by a tractor.

On 10 August 1999, 100 kg / ha 2:3:2 (22) was added to supplement the rapidly growing barley crop. The crop continued to indicate a nitrogen deficiency, hence 130 kg / ha LAN (28% N) was applied on 2 September 1999. Again, the crop persisted to show a nitrogen deficiency, probably caused by the added fodder barley, thus 300 kg / ha 1:0:1 (40) was added on 14 September 1999. Rains followed shortly after each fertilizer application and thus ensured leaching into the surface soil.

On 20 August 1999, each crop strip was sprayed with 1.5 L / ha Grasp herbicide (tralkoxydim as the active ingredient, making up 250 g / L of the herbicide) to eliminate the emerging ryegrass (*Lolium* spp.) from the barley crop. On 7 September 1999, 6.5 L / ha of Banweed MCPA herbicide (phenoxyacetic acid as the active ingredient, making up 400 g / L of the herbicide) was applied to eliminate all broadleaf weeds from the crop. A light infection of rust fungus was sprayed with 200 ml / ha Tilt fungicide (propiconazole as the active ingredient, making up 500 g / L of the fungicide) on 21 September 1999.

Weeds between each crop strip were slashed on 20 August and 1 October 1999. On 10 October 1999, when conditions were fine and mild, 2 L / ha Roundup was sprayed between each crop strip to eliminate weeds in these areas.

2.1.5 Climatic and soil moisture measurements

The weather station operated from 14 September to 9 November 1999 to obtain information concerning variations of wind speed, soil temperature, and soil moisture content in relation to the distance of the southern windbreak. Details were discussed in Section 2.3 $^{\text{Ch. 2}}$.

Soil samples were collected at specific distances from the southern windbreak on 9 November 1999, to provide an insight into the variation of soil moisture content across the site. Samples were collected at 15 to 20 cm below the soil surface. Sampled soil was immediately sealed tightly in a labelled tin. Each tin was weighed, and weighed again following oven drying with lids loosened (at 100°C for 24 hours). Tins were then emptied and weighed. Calculations were made using the following formula:

$$\text{MC (\%)} = (\text{undried soil}^{\text{mass}} - \text{dried soil}^{\text{mass}}) / \text{dried soil}^{\text{mass}} \times 100$$

2.1.6 Windbreak porosity

Windbreak porosity was estimated using two photographs of 3.0 m x 3.0 m samples for each windbreak. Each image was scanned and then posturised by computer. The porosity was calculated using an image digitalisation programme that calculated the number of darker pixels compared to lighter pixels. The porosity of the two images from each windbreak was then averaged.

2.1.7 Statistical methods

Crop data and soil moisture, wind speed, and soil temperature data were analysed by ANOVA. Statistical analysis was done with SAS (SAS Institute Inc., 1985).

2.2 Results

2.2.1 Climatic and soil data

Table 2.2.1 summarises the Munsell colour code descriptions for various distances to the lee of the southern WoS3 windbreak. Table 2.2.2 summarises the means of leaf and stem$^{\text{mass}}$, grain$^{\text{mass}}$, total$^{\text{mass}}$, sub-sample$^{\text{mass}}$ of 100 grains, and proportion of grain$^{\text{mass}}$ from total$^{\text{mass}}$, for barley crops strips located at various distances from the southern WoS3 windbreak. The average porosity of the southern WoS3 windbreak was calculated to be 40%. All following distances described for WoS3 were located to the lee of the southern windbreak.

From the Munsell-colour codes, little difference was observed from 0.0 to 7.0 H to the lee of the windbreak. A lighter and sandier soil occurred from 9.0 to 11.0 H, with granules being coarser than any other part of the site. From 13.0 to 19.0 H, the soil was found to be darker and greyer. Soil at 15.0 H was the darkest soil throughout the site, indicating a higher level of organic matter (Dr. Freddie Ellis, personal communication).

Table 2.2.1 Summary of Munsell colour-code descriptions, for various distances (H)* to the lee of the southern WoS3 windbreak.

distance (H)	*wet Munsell colour code description*	*dry Munsell colour code description*
0.0	10YR42 (dark greyish brown)	10YR54 (yellowish brown)
1.0	10YR42 (dark greyish brown)	10YR54 (yellowish brown)
2.0	10YR42 (dark greyish brown)	10YR54 (yellowish brown)
3.0	10YR42 (dark greyish brown)	10YR54 (yellowish brown)
5.0	10YR42 (dark greyish brown)	10YR54 (yellowish brown)
7.0	10YR43 (brown)	10YR54 (yellowish brown)
9.0	10YR44 (dark yellowish brown)	10YR63 (pale brown)
11.0	10YR43 (brown)	10YR53 (brown)
13.0	10YR33 (dark brown)	10YR53 (brown)
15.0	10YR31 (very dark grey)	10YR42 (dark greyish brown)
17.0	10YR33 (dark brown)	10YR52 (greyish brown)
18.0	10YR32 (very dark greyish brown)	10YR52 (greyish brown)
19.0	10YR32 (very dark greyish brown)	10YR52 (greyish brown)

* Effective tree height (H) was 5.0 m. All distances were located on the leeward side of the windbreak to prevailing winds.

References of threshold levels for barley and potatoes were insufficiently detailed, so estimates were developed from personal communication with Prof. Andre Agenbag and Mr. Jan Lambrechts. From the soils that were analysed at the distances shown in Table 2.2.1, pH (KCl) at all distances (pH ranging from 3.8 to 4.4) was consistently slightly below the optimum level for barley (pH = 5.0 to 6.0), with the exception being at 7.0 H (pH = 6.7). P levels were limiting for barley (below 25 m g/ kg) at 11.0 H (11 mg / kg), and 13.0 and 17.5 H (17 to 18 mg / kg). The Ca:Mg ratio was below the optimum level (4.0 to 6.0) for barley at 9.0, 11.0, 13.0, and 17.5 H (2.8 to 3.3). K (% of S) was limiting (considered below 4.0%) at 11.0, 13.0, and 17.5 H (2.6 to 2.8%). Alkaline resistance, Ca, Mg, and Na were not limiting for barley at any distance across the site (Prof. Andre Agenbag and Mr. Jan Lambrechts, personal communication). Available N levels were lowest at 1.5, 7.0, and 9.0 H (about 1.0, 1.5 to 1.4 respectively), and peaking at 3.0 to 5.0 H (respectively), and 15.0 to 17.5 H (respectively).

2.2.2 Yield data

Table 2.2.2 Summary of the means* of leaf and stem$^{\text{mass}}$, grain$^{\text{mass}}$, total$^{\text{mass}}$, sub-sample$^{\text{mass}}$ of 100 grains, and proportion of grain$^{\text{mass}}$ from total$^{\text{mass}}$, for barley crops strips located at various distances (H) from the southern WoS3** windbreak.

distance (H)	leaf and stem$^{\text{mass}}$ (g)	grain$^{\text{mass}}$ (g)	total$^{\text{mass}}$ (g)	proportion of grain$^{\text{mass}}$ ***	grain sub-sample$^{\text{mass}}$ (g)
1.0	17.23_{a}	11.15_{ab}	28.38_{abc}	0.67_{ab}	2.51_{ab}
2.0	16.27_{ab}	11.86_{ab}	28.14_{abc}	0.72_{a}	2.63_{a}
3.0	19.64_{a}	11.80_{ab}	31.43_{ab}	0.60_{ab}	2.17_{cd}
5.0	15.47_{a}	8.10_{c}	23.57_{cd}	0.53_{ac}	2.30_{bc}
7.0	16.16_{ab}	9.02_{bc}	25.17_{bcd}	0.56_{ac}	2.12_{cd}
9.0	11.25_{d}	5.09_{d}	16.33_{e}	0.46_{cd}	1.85_{de}
11.0	11.94_{cd}	4.49_{d}	16.43_{e}	0.39_{d}	1.68_{e}
13.0	12.72_{bcd}	7.64_{c}	20.36_{ed}	0.58_{abc}	2.06_{cd}
15.0	19.99_{a}	12.79_{a}	32.78_{a}	0.64_{ab}	2.27_{bc}
17.0	18.65_{a}	11.55_{ab}	30.20_{ab}	0.63_{ab}	2.09_{cd}
18.2	16.68_{ab}	5.00_{d}	21.68_{de}	0.29_{e}	1.57_{e}

* Means with the same subscript were not significantly different using the ANOVA method. Subscripts relate to respective columns only.

** Effective tree height (H) was 5.0 m. All distances were located on the leeward side of the windbreak to prevailing winds

*** Subscripts for the proportion of grain$^{\text{mass}}$ from the total$^{\text{mass}}$ is for the transformed square root.

Distance from the southern WoS3 windbreak had a significant effect ($p < 0.05$) for leaf and stem$^{\text{mass}}$, grain$^{\text{mass}}$, total$^{\text{mass}}$, grain sub-sample (100 grains)$^{\text{mass}}$, and proportion of grain$^{\text{mass}}$ from total$^{\text{mass}}$. However, significant interactions between distance and replicates also occurred ($p < 0.05$) for yields of grain$^{\text{mass}}$ and proportion of grain$^{\text{mass}}$ from total$^{\text{mass}}$ in relation to the southern WoS3 windbreak. Figure 2.2.1 illustrates the averaged variation of leaf and stem$^{\text{mass}}$ and also grain$^{\text{mass}}$, in relation to the distance from the southern windbreak. The variation of soil moisture content is also shown. Yields are given as averages.

Leaf and stem$^{\text{mass}}$ was significantly lower ($p < 0.05$) at a distance of 9.0 H (11.2 g) than all other treatments except for 11.0 and 13.0 H. Leaf and stem$^{\text{mass}}$ was significantly higher ($p < 0.05$) at a distance of 1.0, 3.0, 15.0, and 17.0 H (17.2 to 20.0 g) than at 9.0, 11.0 and 13.0 H (11.2 to 12.7 g). Grain$^{\text{mass}}$ was significantly lower ($p < 0.05$) at a distance of 9.0, 11.0, and 18.2 H (4.49 to 5.09 g) than all other treatments. Grain$^{\text{mass}}$ was significantly higher ($p < 0.05$) at a distance of 1.0, 2.0, 3.0, 15.0, and 17.0 H (11.15 to 12.79 g) than all other treatments except for 7.0 H. However, as mentioned earlier, interaction was significant. Total$^{\text{mass}}$ was significantly lower ($p < 0.05$) at a distance of 9.0 and 11.0 H (16.3 to 16.4 g) than all other treatments except for 13.0 and 18.2 H.

Figure 2.2.2 illustrates the averaged variation of sub-sample grain$^{\text{mass}}$, in relation to the distance from the southern windbreak. The sub-sample$^{\text{mass}}$ of 100 grains was significantly higher ($p < 0.05$) at a distance of 2.0 H (2.63 g) than all other treatments except at 1.0 H. Sub-sample$^{\text{mass}}$ of 100 grains was significantly lower ($p < 0.05$) at a distance of 11.0 and 18.2 H (1.57 to 1.68 g) than all other treatments except for 9.0 H. Yields for the proportion of grain$^{\text{mass}}$ from the total$^{\text{mass}}$ were significantly lower ($p < 0.05$) at a distance of 18.2 H (0.29) than all other treatments. However, as mentioned earlier, interaction was significant.

Severe flattening of barley beyond 9.0 H occurred following the gale-force winds that occurred from 16 to 20 October 1999. Plates A2.1 and A2.2 in Section 6$^{\text{Ch. 3}}$compare the intact sheltered crop at 2.0 H with the damaged unsheltered crop at 11.0 H (as observed on 21 October 1999).

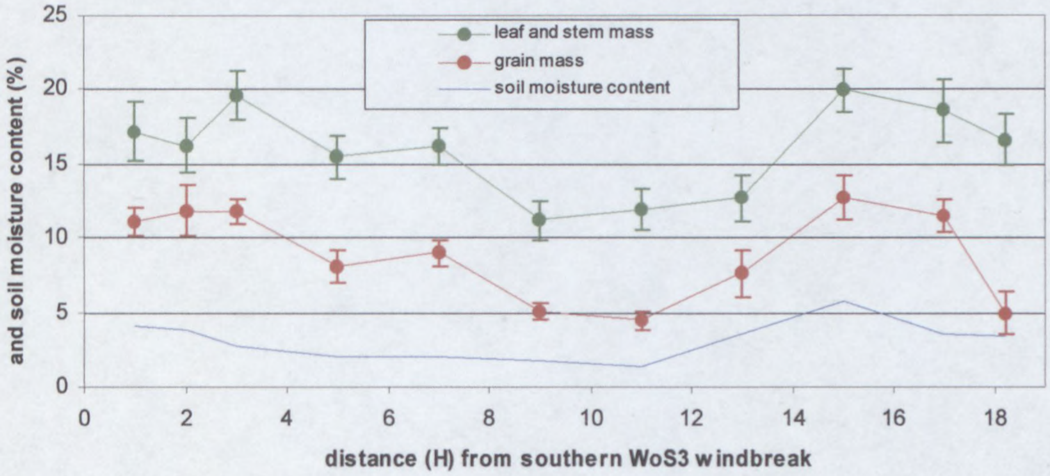

Figure 2.2.1 Averaged variation of leaf and stem$^{\text{mass}}$ and also grain$^{\text{mass}}$, in relation to the distance from the southern *C. cunninghamiana* windbreak at WoS3. Effective tree height (H) was 5.0 m. Error bars indicate the level of the 95% confidence interval for each treatment. The variation of soil moisture content is also shown. Data points have been joined to enhance visual presentation.

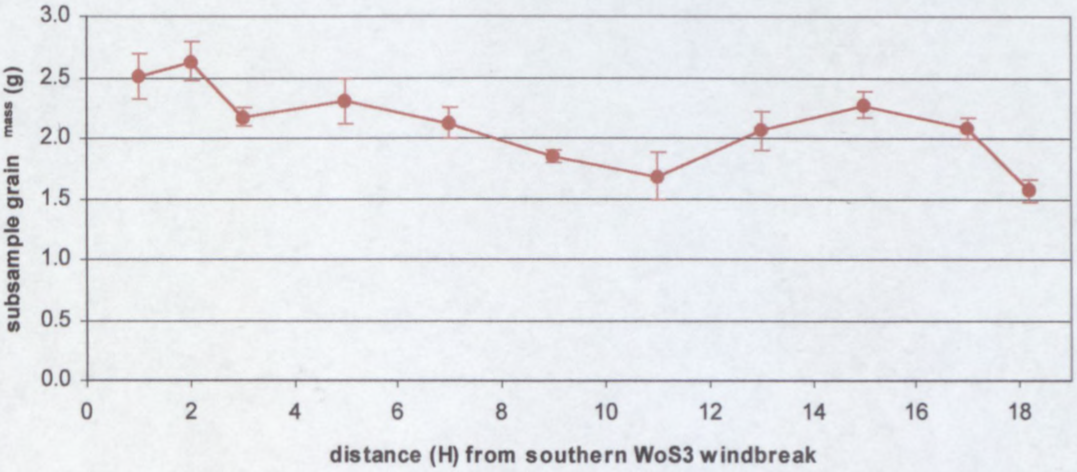

Figure 2.2.2 Averaged variation of sub-sample grain$^{\text{mass}}$, in relation to the distance from the southern *C. cunninghamiana* windbreak at WoS3. Effective tree height (H) was 5.0 m. Error bars indicate the level of the 95% confidence interval for each treatment. Data points have been joined to enhance visual presentation.

2.3 Discussion

2.3.1 Shelter effect

All following distances described for WoS3 were located to the leeward side of the southern WoS3 windbreak. Distance from the southern WoS3 windbreak had a significant effect ($p < 0.05$) for leaf and stem^{mass}, grain^{mass}, sub-sample^{mass} of 100 grains, total^{mass}, and proportion of grain^{mass} from total^{mass} (Table 2.2.2 in Section 2.2.2$^{Ch.\ 3}$). Significant interactions between distance and replicates ($p < 0.05$) also occurred for the latter two variables. Figure 2.2.1 in Section 2.2.2$^{Ch.\ 3}$ illustrates the averaged variation of leaf and stem^{mass} and also grain^{mass}, in relation to the distance from the southern windbreak. The variation of soil moisture content is also shown.

The general decrease in yields (leaf and stem^{mass}, grain^{mass}, and proportion of grain^{mass} from total^{mass}) from 3.0 to 11.0 H might have suggested a pronounced reponse to a decrease in the shelter effect in a leeward direction from the WoS3 windbreak. However, the recovery of the high yields at 15.0 and 17.0 H suggested that reduced yields at 7.0 and 11.0 H were attributed more to the effect of soil variation than wind speed variation. The presence of a slight depression line meandering through the site at 15.0 H was the main cause of a higher soil moisture content and the inherently higher fertility at 15.0 H, compared to other locations. These different soils were evident on the aerial photograph in Plate 2.2.1 in Section 2.1.3$^{Ch.\ 3}$. Figure 2.2.1 in Section 2.2.2$^{Ch.\ 3}$ illustrates a high correlation between crop yield and soil moisture content. The lowest yields occurred from 9.0 to 13.0 H, where the worst structured and coarsest sandy soil occurred. Soil in this zone tended to have relatively low P, K, and Ca : Mg levels, as described in the last paragraph of Section 2.2.1$^{Ch.\ 3}$.

Also, the delayed occurrence of the seasonal south-easterly wind until so late in the growing season restricted the propensity of the winds to have a significant shelter effect. Seasonal variation of the shelter effect might be due to variations in the frequency, intensity, and orientation of damaging winds (Nuberg, 1998; Pretzechel *et al.*, 1991). Poor display of the shelter effect occurs in seasons where the microclimate conditions in the exposed zone are very favourable and the advantage of shelter was minimal, or when the advantages gained through shelter are negated by weather events later in the season.

The combined influences of soil variations (or more specifically, soil surface elevation) and the late occurrence of the severe south-easterly winds masked the shelter effect on the WoS3 crop. Despite the obscurity of a general windbreak effect on crop yields, there was some evidence of such an effect.

At first glance, the general decrease in yields (leaf and stem^{mass}, grain^{mass}, and proportion of grain^{mass} from total^{mass}) from 3.0 to 11.0 H might have suggested a pronounced response to a decrease in the shelter effect in a leeward direction from the WoS3 windbreak. Indeed, WoS3 winds speeds summarised in Section 3.1.2$^{Ch. 2}$ were lowest at 1.0 and 3.0 H, intermediate at 7.0 H, and highest at 11.0 and 13.0 H from the southern WoS3 windbreak. The leeward extent of the maximum shelter effect was estimated to extend from 3.0 to 6.0 H (Cleugh and Hughes, 2000; Cleugh, 1998; Sun and Dickinson, 1997; Hodges and Brandle, 1996; Bird, 1988; Ujah and Adeoye, 1984). However, the recovery of the high yields at 15.0 and 17.0 H suggests that reduced yields at 7.0 and 11.0 H were attributed more to the effect of soil variation than wind speed variation.

To block out the soil effect, crop yields at 2.0 and 17.0 H were directly compared with each other as the soils were similar, as indicated by the Munsell colour codes and the soil analysis described in Section 2.2.1$^{Ch. 3}$. The soil moisture content at 2.0 and 17.0 H was also similar, as indicated in Figure 2.2.1 (Section 2.2.2$^{Ch. 3}$). Hence, the similar soils at 2.0 and 17.0 H suggested that any differences in yield between these two locations were attributed to different wind speeds. However, leaf and stem^{mass}, grain^{mass}, total^{mass}, and the proportion of grain^{mass} from total^{mass} was not significantly different ($p > 0.05$) between the two locations at 2.0 and 17.0 H.

Therefore, the occurrence of severe south-easterly winds was too late to affect most stages of the crops growth. However, the last stage of growth (the process of grain filling) might have been affected, as indicated in the next paragraph. Variations of leaf and stem$^{\text{mass}}$, grain$^{\text{mass}}$, and proportion of grain$^{\text{mass}}$ from total$^{\text{mass}}$ recorded across the site were attributed to the effect of soil variation. Therefore, the soils from 1.0 to 7.0 H and from 15.0 to 18.2 H were similarly productive; and in most cases notably more productive than the soil from 9.0 to 13.0 H. The yields at 18.2 H were not included in the comparisons because this location experienced an effect that was unique to the site, described in the following section.

The best indication of a possible shelter effect was from the variation of the sub-sample$^{\text{mass}}$ of 100 grains. A summary of the data is shown in Table 2.2.2 and illustrated in Figure 2.2.2 in Section 2.2.2$^{\text{Ch. 2}}$. The highest yields were observed at 1.0, 2.0, and 5.0 H, which were greater than any other yield across the site.

This observation was notable when considering that the yields for the other variables were consistently highest at 15.0 H, compared to other distances from the windbreak. Only the sub-sampled$^{\text{mass}}$ of 100 grains at 2.0 H was significantly greater than that at 15.0 H. The capacity for the sub-sampled$^{\text{mass}}$ of 100 grains at 1.0, 2.0, and 3.0 H to at least match that at 15.0 H was a possible indication of an improvement of crop water-use efficiency.

The similar soils at 2.0 and 17.0 H suggested that differences in sub-sampled$^{\text{mass}}$ of 100 grains at these two locations were attributed to different wind speeds. Sub-sampled$^{\text{mass}}$ of 100 grains significantly increased ($p < 0.05$) from an average 2.09 g at 17.0 H to 2.63 g at 2.0 H, a 20.5% increase attributed to the shelter effect.

Despite a more productive soil at 15.0 H compared to that at 2.0 H, the sub-sampled$^{\text{mass}}$ of 100 grains was still significantly higher ($p < 0.05$) at 2.0 H. Sub-sampled$^{\text{mass}}$ of 100 grains significantly increased ($p < 0.05$) from an average 2.27 g at 15.0 H to 2.63 g at 2.0 H, a 13.7% increase attributed to the shelter effect overcoming the soil effect. This shelter effect was further evidenced by the observation of earlier wilting and drying of barley in the more exposed zones than in the sheltered zones. The barley at 1.0 to 5.0 H remained considerably greener compared to barley at any other distance, as illustrated in Plates A2.1 and A2.2 in Section 6$^{\text{Ch. 3}}$. Therefore, despite better soil conditions at 15.0 H, there were indications that a shelter effect up to 7.0 H compensated for the less productive soils in the sheltered zone by improving the microclimate. This estimated extent of crop shelter at WoS3 was notably similar to that estimated at ViS1 in Section 1.3.2.4 $^{\text{Ch. 3}}$.

The effect of water stress on crop yield is greater at different stages of plant development than others. For example, water stress at the pre-jointing stage of wheat development may restrict the development of tillers; water stress at the double-ridging stage may restrict the development of grain heads; and water stress at grain filling will limit final grain yield (Nuberg, 1998; Hough and Cooper, 1988). Hot and dry winds during grain filling reduce yields by causing a rapid loss of grain water content (Smika and Shawcroft, 1980). As the drier conditions at WoS3 followed crop anthesis, it was possible that improved water conservation due to the shelter effect only occurred during the period of grain filling.

The period of photosynthetic activity increases in the sheltered zone, owing to the delay of wilting and hence an increase in net assimilation (Puri *et al.*, 1992). Damage to leaf surfaces decreased the ability of a plant to control water loss by stomatal control. The damaged cuticle also pre-disposed the leaf to pollution stress or invasion by pathogens (Grace, 1988). Physical damage to wheat leaves caused a twofold or greater increase in leaf conductance. Further damage resulted when wind carried particles of sand (Armburst, 1984). Shelter reduced transpiration and perhaps soil evaporation, and subsequently the soil moisture conserved by this process was then available for crop use later in the growing season (Nuberg, 1998).

Another indication of the shelter effect was from the distribution of fallen or broken barley stems during the time of yield sampling. During the two weeks before sampling, the entire crop had dried. Although the growing season had ended, potentially severe winds had continued in the exposed zones. This had resulted in a general lean of the crop (in the direction of the south-easterly winds), from 7.0 H and beyond. In many instances stem breakage had occurred, resulting in fallen or hanging grain heads. No such lean was observed from 1.0 to 5.0 H. For taller crops (especially crops with filled grain heads), the force of the wind tends to lodge the crop either by breaking stems or by causing the collapse of the soil and roots. Fallen crops are difficult to harvest and grain recovery may become uneconomical. Also, crops left to dry in the field after harvest can be blown away, or lose yield due to seed shattering in strong winds (Kort, 1988). Therefore, the crop benefits of a shelter effect can extend beyond the growing period of the crop.

2.3.2 Competition effects

All following distances described for WoS3 were located to the leeward side of the southern WoS3 windbreak. A summary of the relevant crop data is shown in Table 2.2.2 and illustrated in Figure 2.2.1 (Section 2.2.2$^{\text{Ch. 3}}$). Low yields at 18.2 H (compared to those at 17.0 H) were attributed to shading from the adjoining northern windbreak (18.8 H from the southern windbreak). Shade from solar radiation directly affects plant growth because of the reduction of photosynthetically active radiation and indirectly because of its effects on soil and air temperatures and evaporation (Abel *et al.*, 1997).

Crop yields at 17.0 and 18.2 H from the southern windbreak could be directly compared with each other as the soils were similar, as indicated in the Munsell colour codes and the soil analysis described in Section 2.2.1$^{\text{Ch. 3}}$. The soil moisture content at 17.0 and 18.2 H was also similar, as indicated in Figure 2.2.1. Compared to the leeward yields at 17.0 H, those at 18.2 H were significantly reduced ($p < 0.05$) for grain$^{\text{mass}}$ (by an average of 57%), total$^{\text{mass}}$ (28%), proportion of grain$^{\text{mass}}$ from total$^{\text{mass}}$ (28%), and sub-sampled$^{\text{mass}}$ of 100 grains (24%, dropping from 2.09 to 1.57 g).

Leaf and stem$^{\text{mass}}$ was reduced by an average of 11% at 18.2 H, compared to 17.0 H. However, the difference was not significant ($p > 0.05$), perhaps suggesting that (unlike grain production) vegetative production of barley was not affected by shade. Figure 2.2.1 in Section 2.2.2$^{\text{Ch. 3}}$ illustrates these differences for leaf and stem$^{\text{mass}}$ and grain$^{\text{mass}}$, between 17.0 and 18.2 H. Figure 2.2.2 in Section 2.2.2$^{\text{Ch. 3}}$ illustrates the difference for sub-sampled$^{\text{mass}}$ of 100 grains between 17.0 and 18.2 H.

The rapid recovery of yields at 17.0 H (compared to the yields at 18.2 H) indicated that the competitive effect was highly restricted. Windbreaks generally caused a reduction in crop growth up to 1.5 to 2.0 H from the trees (Kowalchuk and De Jong, 1995; Puri *et al.*, 1992; Baldwin, 1988; Lyles *et al.*, 1984). Past evidence indicated maximum yield gains were typically found in the leeward sheltered zone between 3.0 and 10.0 H (Cleugh, 1998). Further investigations concerning the extent of competition were discussed in Section $1.3.6.3^{\text{Ch. 2}}$.

The absence of a competition effect on the northern side of the southern WoS3 windbreak, and the similarity of soil moisture content (Figure 2.2.1 in Section $2.2.2^{\text{Ch. 3}}$) and soil nutrient levels at 17.0 and 18.2 H, suggest that the competitive interaction did not occur below the soil surface. Therefore, the competitive effect was attributed to longer periods of shading of the crop by the northern windbreak, in much the same way that was described for ViS1 in Section $1.3.6.3^{\text{Ch. 2}}$. Other investigations concerning the mechanism of the shading effect were also discussed in Section $1.3.6.3^{\text{Ch. 2}}$.

2.4 Conclusions of microclimate variation at WOS3

2.4.1 Shelter effect

Distance from the southern WoS3 windbreak had a significant effect ($p < 0.05$) for yields from leaf and stem$^{\text{mass}}$, grain$^{\text{mass}}$, sub-sample$^{\text{mass}}$ of 100 grains, total$^{\text{mass}}$, and proportion of grain$^{\text{mass}}$ from total$^{\text{mass}}$. The general decrease in yields (leaf and stem$^{\text{mass}}$, grain$^{\text{mass}}$, and proportion of grain$^{\text{mass}}$ from total$^{\text{mass}}$) from 3.0 to 11.0 H might have suggested a pronounced response to a decrease in the shelter effect in a leeward direction from the WoS3 windbreak. However, the recovery of the high yields at 15.0 and 17.0 H suggested that reduced yields at 7.0 and 11.0 H were attributed more to the effect of soil variation than wind speed variation.

The presence of a slight depression line meandering through the site at 15.0 H was the main cause of a higher soil moisture content and the inherently higher fertility at 15.0 H, compared to other locations. The combined influences of soil variations (or more specifically, soil surface elevation) and the late occurrence of the severe south-easterly winds masked the shelter effect on the WoS3 crop.

The similar soils at 2.0, 17.0, and 18.2 H suggested that any differences in yield between these locations were attributed to different wind speeds. The best indication of a possible shelter effect was from the variation of the sub-sample^{mass} of 100 grains, where the yield at 2.0 H was significantly higher ($p < 0.05$) at 2.0 H, compared to that at 17.0 H. Compared to 17.0 H, the sub-sampled^{mass} of 100 grains was significantly higher ($p < 0.05$) at 2.0 H. Sub-sampled^{mass} of 100 grains increased from an average of 2.09 g at 17.0 H to 2.63 g at 2.0 H, a 20.5% increase attributed to the shelter effect.

Despite a more productive soil at 15.0 H compared to that at 2.0 H, the sub-sampled^{mass} of 100 grains was still significantly higher ($p > 0.05$) at 2.0 H. Sub-sampled^{mass} of 100 grains increased from an average of 2.27 g at 15.0 H to 2.63 g at 2.0 H, a 13.7% increase attributed to the shelter effect overcoming the soil effect. This shelter effect was further evidenced by the observation of earlier drying of barley in the more exposed zones than in the sheltered zones.

Compared to 2.0 H, yields at 17.0 H were not significantly different ($p > 0.05$) for leaf and stem^{mass}, grain^{mass}, total^{mass}, and the proportion of grain^{mass} from total^{mass}. Therefore, the occurrence of severe south-easterly winds was too late to affect vegetative growth of the barley crop. However, the last stages of growth were affected (indicated by the sub-sampled^{mass} of 100 grains).

2.4.2 Competition effect

Crop yields at 17.0 and 18.2 H from the southern windbreak could also be directly compared as the soils were similar. Compared to the leeward yields at 17.0 H, those at 18.2 H were significantly reduced ($p < 0.05$) for grain^{mass} (by an average of 57%), total^{mass} (28%), proportion of grain^{mass} from total^{mass} (by 28%), and sub-sampled^{mass} of 100 grains (by 24%). Leaf and stem^{mass} was reduced by an average of 11% at 18.2 H, compared to

17.0 H. However, the latter difference was not significant ($p > 0.05$), perhaps suggesting that (unlike grain production) vegetative production of barley was not affected by shade.

The rapid recovery of yields at 17.0 H (compared to the yields at 18.2 H) indicated that the competitive effect was highly restricted. The absence of a competition effect on the northern side of the southern windbreak, and the similarity of soil moisture content and soil nutrient levels at 17.0 and 18.2 H, suggest that the competitive interaction did not occur below the soil surface.

3 SARON SITE 1 (SaS1)

3.1 Method

3.1.1 Regional description

SaS1 was located 4 km south-west of Saron (latitude 18°58′E, longitude 33°12′S, altitude 115 m) on the "Tweerivieren" farm of Ben van Niekerk and manager Vincent du Plessis. Plate 1.1 in Section 3.2 $^{\text{Ch. 1}}$ illustrates the location of SaS1 in the Western Cape Region. Enterprises on the property included crops of wheat, oats, lupins, and a small amount of vegetable and vineyard cultivation. The farm is flat to mildly undulating.

Table 2.3.1 shows the summarised long term and 1998 data collected from the "De Hoek" DWAF weather station, located 4 km north of Tweerivieren farm. The average yearly long-term wind speed at Saron was 171 km / day. Average wind speeds were highest between October and March, during which time the south-easterly winds dominated. Less severe, but nevertheless strong, north-westerly winds occurred during winter. The average daily maximum temperature in this area was 31.5°C for the hottest month (February) and the average daily minimum temperature for the coolest month (July) was 7.9°C. The site is in a temperate winter rainfall area, with June having the highest average monthly rainfall (108.3 mm), and January having the lowest average monthly rainfall (8.9 mm). Data for total evaporation and Relative Humidity (RH) are also included in Table 2.3.1.

Table 2.3.1 Long-term records and 1998 records of weather data recorded at the "De Hoek" weather station near Saron.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Long term av. wind speed (km / day)	223.2	225.5	209.6	165.2	105.4	98.8	107.3	133.2	158.0	204.3	205.9	216.2
1998 av. wind speed (km / day)	162.5	190.9	167.9	106.9	86.6	79.6	135.9	130.5	186.3	209.6	196.6	224.6
1998 av. max. wind speed (km / day)	439.9	531.1	664.5	382.7	296.7	240.2	343.7	378.9	526.2	594.2	383.0	534.2
Long term av. daily max. temp. (°C)	31.3	31.5	29.3	25.6	22.4	18.9	18.3	19.2	21.7	24.7	27.0	29.6
Long term av. daily minimum temp. (°C)	17.2	17.7	16.5	13.7	10.9	8.5	7.9	8.5	10.4	12.2	14.1	16.2
1998 av. daily maximum temp. (°C)	30.4	32.6	29.4	26.8	21.1	18.9	18.5	20.1	21.3	25.4	26.6	30.1
1998 av. daily minimum temp. (°C)	16.7	19.2	16.6	14.2	10.3	7.7	8.6	8.4	10.1	12.5	14.1	17.4
Long term av. total rain (mm)	8.9	15.5	25.2	52.2	76.1	108.3	92.8	77.9	54.8	36.4	27.3	23.5
1998 total rain (mm)	22.0	1.5	3.5	18.8	153.0	62.0	71.0	50.1	37.0	20.5	60.3	42.0
Long term av. total evaporation (mm)	310.4	253.9	222.8	133.2	81.8	55.0	62.6	83.0	123.3	198.2	242.7	285.9
1998 total evaporation (mm)	294.0	260.5	210.0	122.3	63.0	36.9	69.5	87.8	127.0	211.0	207.3	263.0
Long term av. daily max. RH (%)	81.1	79.7	81.1	84.4	89.4	91.7	91.0	90.7	89.4	82.2	81.7	81.7
1998 av. daily max. RH (%)	76.9	77.2	74.6	75.2	92.1	94.4	86.0	88.0	80.8	63.1	80.8	73.9

3.1.2 Site description

An aerial view of SaS1 is illustrated in Plate 2.3.1, and a profile view of the SaS1 windbreak with the adjoining wheat field is illustrated in Plate 1.4 in Section 3.2 Ch. 1. This windbreak was located 500 m from the main entrance to the farm, within 100 m south of the main access road. A 13-year old *Eucalyptus cladocalyx* windbreak (average effective height (H) at 12.0 m) was well orientated to provide shelter against the prevailing north-westerly and south-easterly winds. The extensive windbreak was approximately 4 m wide (4 rows in a non-staggered pattern). Trees were spaced at 1.5 m along each row, and each row was 1.5 m apart. Many trees had shed their lower branches up to 4 m in height.

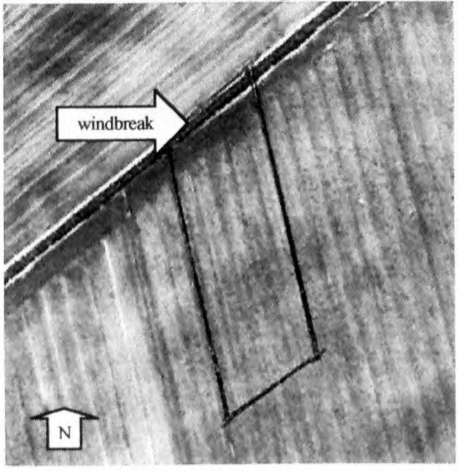

Plate 2.3.1 Aerial view of SaS1. Prevailing winds were north-westerly. Scale 1:7500

Livestock was grazing most of the crops surrounding this windbreak during 1998, particularly the field immediately north of the SaS1 windbreak. Initially it was thought that fenced (cattle proof) plots could be arranged in transects perpendicular to the windbreak on both sides of the windbreak. However, using adequate cage techniques are expensive and time consuming (Bird, 1998), hence this approach was not considered further. Nevertheless, it was suspected that this windbreak would offer protection to the southern ungrazed field, from north-westerly winds during winter and spring.

Soil pits were excavated on 21 August 1998 at three points within the research site, each to a depth of 50 cm. The soil was classified as a Cartref 1100 soil type, with a Klapmuts transitional form (Munsell Color Co., 1975). Each soil profile revealed:

1. An orthic material that was hard setting in a dry state (A horizon) at 0 to 15 cm depth, about 16% clay content, a fine sand grade, and fine gravel fragments (40 to 60%).
2. A material that was hard setting in a dry state (E horizon) at 15 to 30 cm depth, about 16% clay content, a fine sand grade, and fine gravel fragments (40 to 60%).
3. A litho / pedocutanic material with signs of wetness (B horizon) at > 30 cm depth, > 30% clay content, a fine sand grade, and shale fragments (40 to 50%).

Soil was also sampled from the inner three replicates on 4 October 1999 to a depth of 10 to 20 cm. Each collected sample was a composition of soil collected from the centre of the three replicates at 1.0, 2.0, 10.0, and 20 H to the leeward side of windbreak. Each composite sample was sealed in a labelled paper bag, and then air-dried for 7 days. The dried soil was then analysed for the content of available-N, exchangeable cations (Na+, Ca++, P++, K+), and pH. A Munsell colour-code description was made for each soil sample (in both the wet and dry state) to provide further information concerning soil homogeneity across the site.

3.1.3 Experimental design

Plate 2.3.2 illustrates the plan of the SaS1 experimental crop design. The wheat field was arranged in a series of parallel 15 m wide crop strips, each being separated by a narrow drainage line. The raised crop strips provided well-drained beds of soil for the crop. The experimental design extended to 300 m (25.0 H) length on the leeward side of the windbreak. A group of five inner crop strips (each orientated southwards) were selected, producing an experimental design that was 75 m (15 m wide strips x 5 replicates) wide and 300 m long. A sampling transect was positioned in the central region of each crop strip.

On the leeward side also, a single crop strip running parallel and next to the windbreak was included in the experimental design. Thus for each replicate, the line from which the transect was positioned was extended so that a plot could be harvested at 1.0 H from the windbreak as well. This position was located on the central region of the crop strip running parallel to the windbreak. Along each transect, 8 plots (each 0.5 m x 0.5 m) were designated at 12.0, 24.0, 36.0, 60.0, 120.0, 180.0, 240.0, and 300.0 m (1.0, 2.0, 3.0, 5.0, 10.0, 15.0, 20.0, and 25.0 tree heights (H) respectively) to the lee of the windbreak.

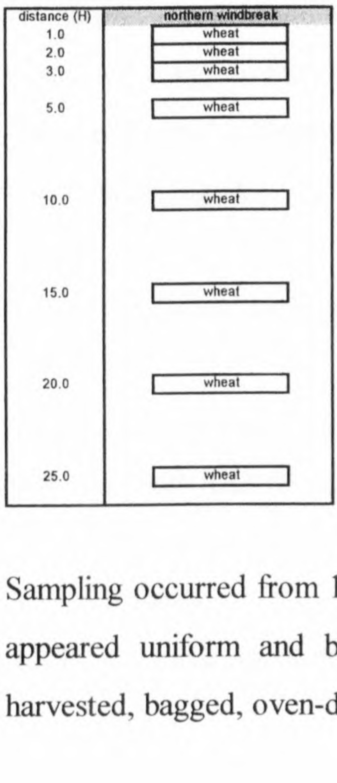

Plate 2.3.2 Plan of SaS1 experimental crop design.

Sampling occurred from 12 to 18 August 1998. At the time of sampling, the entire crop appeared uniform and beginning anthesis. Above-ground ^{mass} within each plot was harvested, bagged, oven-dried (at 100°C), and weighed.

3.1.4 Site preparation

This southern field was sowed with 120 kg / ha wheat (*Triticum aestivum* cultivar SST57) and 380 kg / ha 4:1:1 (33%) N:P:K on 30 April 1998. A supplement of 50 kg / ha Nitro-S (40% N, 6% S) was applied on 2 July 1998.

3.1.5 Wind speed and soil moisture measurements

No such measurements were made, as the portable weather station was unavailable for use at SaS1 during 1998.

3.1.6 Windbreak porosity

Windbreak porosity was estimated using two photographs of 3 m x 3 m samples for each windbreak. Each image was scanned and then posturised by computer. The porosity was calculated using an image digitalisation programme that calculated the number of darker pixels compared to lighter pixels. The porosity of the two images from each windbreak was then averaged.

3.1.7 Statistical methods

Wheat yield data were analysed by Analysis of Variance (ANOVA). Statistical analysis was done with SAS (SAS Institute Inc., 1985).

3.2 Results

3.2.1 Climatic and soil data

From the regional DWAF weather station, records indicated that average monthly wind speeds during the crop's growing period in 1998 were consistent with long-term records (Table 2.3.1 in Section 3.1.1 $^{\text{Ch. 3}}$). The average maximum wind speed during 1998 was 443 km / day. Higher maximum wind speeds generally occurred in the late summer months due to the prevalence of south-easterly winds, peaking in March 1998 and dropping sharply from April to August 1998. The average wind speed during 1998 of 156 km / day was below the long-term average of 171 km / day. Of all the sites described in this project, Saron had the lowest winter / early spring maximum wind speeds.

Average daily temperatures for each month were similar to the long-term records. The highest average daily maximum temperature in this region during 1998 was recorded in February (32.6°C) and the lowest average daily minimum temperature was recorded in June (7.7°C). Rainfall was very high in May 1998 (153.0 mm), but below average throughout winter and spring. Total evaporation and average daily RH during 1998 were consistent with long term records.

Table 2.3.2 summarises the Munsell colour-code descriptions for various distances to the lee of the SaS1 windbreak. Table 2.3.3 summarises the above-ground$^{\text{mass}}$ for various distances to the lee of the SaS1 windbreak. The average porosity of the SaS1 windbreak (above 3 m height) was calculated to be 33%.

Table 2.3.2 Summary of Munsell colour-code descriptions, for various distances (H)* to the lee of the SaS1 windbreak.

Distance (H)	*Wet Munsell colour code description*	*Dry Munsell colour code description*
1	10YR58 (yellowish brown)	10YR74 (very pale brown)
2	10YR56 (yellowish brown)	10YR83 (very pale brown)
10	10YR44 (dark yellowish brown)	10YR83 (very pale brown)
25	10YR44 (dark yellowish brown)	10YR83 (very pale brown)

* Effective tree height (H) was estimated to be 12.0 m. All distances were located on the leeward side of the windbreak to prevailing winds.

From the soils that were analysed at distances of 1.0, 2.0, 10.0, and 25.0 H to the lee of the northern SaS1 windbreak, pH (KCl) at all distances (ranging from 3.9 to 4.3) was consistently slightly below the optimum level (pH = 4.5) for wheat. P levels (ranging from 16 to 21 mg / kg) were consistently slightly below the optimum level (25 mg / kg) for wheat. The Ca : Mg ratio was below the optimum level (4.0 to 6.0), increasing from 1.8

to 2.6 from 25.0 to 1.0 H respectively. K (% of S) ranged from 3.8 to 5.2%, which was close to the optimum level of 4%. For all soil samples, alkaline resistance, Ca, Mg, and Na were not limiting for wheat. In summary, the pH, available N, P, and K levels were mildly limiting for wheat, but consistent across the site (Prof. Andre Agenbag and Mr. Jan Lambrechts, personal communication). The uniformity across the site is also indicated by the consistent Munsell colour-codes shown in Table 2.3.2.

3.2.2 Yield data

Table 2.3.3 Summary of the means* of above-ground^{mass}, for various distances (H)** to the lee of the SaS1 windbreak.

Distance (H)	Wheat above-ground^{mass} (g)
1	64.23_{d}
2	171.35_{a}
3	141.19_{abc}
5	148.92_{abc}
10	162.90_{ab}
15	126.95_{bc}
20	115.31_{c}
25	167.60_{ab}

* Means with the same subscript were not significantly different using the ANOVA method.

** Effective tree height (H) was estimated to be 12.0 m. All distances were located on the leeward side of the windbreak to prevailing winds.

Leeward distance from the windbreak had a significant effect ($p < 0.05$) on wheat above-ground^{mass}. The lowest average above-ground^{mass} (64.2 g) was recorded at 1.0 H, which was significantly lower than at any other distance from the windbreak. The highest average yields of above-ground^{mass} (162.9 to 171.4 g) were recorded at 2.0, 10.0, and 25.0 H respectively. Figure 2.3.1 illustrates the averaged variation of above-ground^{mass}, in relation to the SaS1 windbreak.

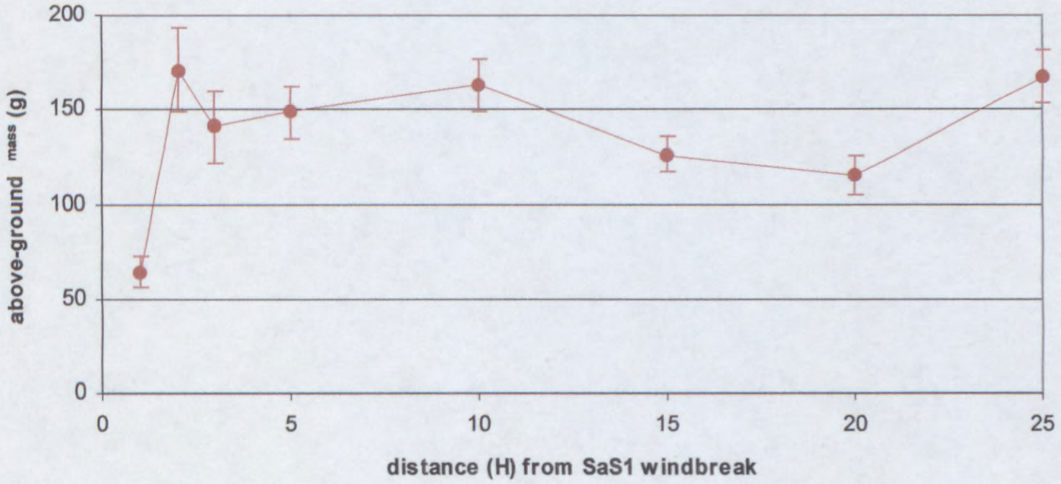

Figure 2.3.1 Averaged variation of above-ground^{mass}, in relation to the northern *E. cladocalyx* windbreak at SaS1. Effective tree height (H) was 12.0 m. Error bars indicate the level of the 95% confidence interval for each treatment. Data points have been joined to enhance visual presentation.

3.3 Discussion

3.3.1 Shelter effect

Although average wind speeds (recorded by the nearby DWAF weather station) dropped sharply in the winter months, relative to the summer months, maximum wind speeds remained severe throughout 1998 (Table 2.3.1 in Section 3.1.1$^{Ch. 3}$). Therefore, a shelter effect was potentially a significant benefit at SaS1. No wind speed data from the portable weather station were available during the assessment of crop yields at SaS1.

However, there was little possibility of a shelter effect at SaS1 due to the 4 m high gaps in the lower profile of the windbreak. Gaps in the windbreak profile channel the wind and actually increase the wind speed, and subsequently contribute to soil erosion and crop damage on the downwind side (Rocheleau *et al.*, 1988; Myburgh and Viljoen, 1979). Cattle that browsed the lower 2 m of foliage of unfenced cypress increased wind speeds by 33%, compared to the unsheltered zone (Bicknell, 1991).

The absence of a shelter effect at SaS1 was immediately suspected, but further analysis proceeded to develop assessment techniques for subsequent sites. SaS1 was not considered for further assessment in 1999 because of the more effective windbreaks that were subsequently identified at WoS3 and ViS1.

The lack of a general trend for above-ground$^{\text{mass}}$ in relation to the distance from the windbreak also suggested that the shelter effect was negligible (Table 2.3.3 and Figure 2.3.1 in Section 3.2.2$^{\text{Ch. 3}}$). The absence of crop damage at all distances from the windbreak was a further indication of an insignificant shelter effect, as well as an indication that maximum wind speeds across the site, although severe, were not notably damaging to the crop. The above-ground$^{\text{mass}}$ fluctuations that occurred from 2.0 to 25.0 H were more likely due to very localised soil variations than to any wind speed variation.

Slight variations of clay content probably influenced the level of waterlogging on a localised scale. This might explain why crop growth was superior at the edges of the crop strips, where drainage was greatest. This influence of soils with high clay contents was a major reason for the preference of sandier soils at subsequent sites. Soil nutrient levels across the site were low but consistent; and therefore the crop variation was most likely due to waterlogging variation. The Munsell colour code summary in Table 2.3.2 of Section 3.2.1$^{\text{Ch. 3}}$ also suggested a generally consistent soil. The large difference in the respective wet and dry codes for each sampled soil indicated a high level of oxides, i.e. evidence of the high clay content in the soil at SaS1.

3.3.2 Competition effect

Considering the ineffectiveness of the SaS1 windbreak to provide shelter, it was almost surprising to observe a significant competition effect ($p < 0.05$) occurring at 1.0 H, relative to all other distances from the windbreak (Table 2.3.3 and Figure 2.3.1 in Section 3.2.2$^{\text{Ch. 3}}$). Above-ground$^{\text{mass}}$ from 2.0 to 25.0 H (averaging from 115.3 to 171.4 g) was significantly higher ($p < 0.05$) than that recorded at 1.0 H (averaging 64.2 g). The similar soil conditions between 1.0 and 2.0 H (Section 3.2.1 $^{\text{Ch. 3}}$) indicated that the poor crop growth at 1.0 H was not due to a soil effect.

Low yields at 1.0 H (compared to those at 2.0 H) were attributed to shading from the adjoining northern windbreak. Shade from solar radiation directly affects plant growth because of the reduction of photosynthetically active radiation and indirectly because of its effects on soil and air temperatures and evaporation (Abel *et al.*, 1997). Further references are shown in the last 5 paragraphs of Section 1.3.6.3 $^{\text{Ch. 2}}$. The extent of below-ground competition was probably negligible, as soil moisture levels were not considered to be limiting during the winter growth period.

Due to the consistent soils at 1.0 and 2.0 H, crops yields could be directly compared with each other. Compared to the above-ground $^{\text{mass}}$ at 2.0 H, those at 1.0 H were significantly reduced ($p < 0.05$) by 44%. The highest above-ground $^{\text{mass}}$ across the site was recorded at 2.0 H, hence the competition effect was restricted to 1.0 H from the windbreak. This magnitude and extent of competition at SaS1 was consistent with the observations observed on the southern side of the ViS1 and WoS3 windbreaks, described in Section 1.3.6.3 and Section 2.3.2 $^{\text{Ch. 2}}$ respectively. Windbreaks generally caused a reduction in crop growth up to 1.5 to 2.0 H from the trees (Kowalchuk and De Jong, 1995; Puri *et al.*, 1992; Baldwin, 1988; Lyles *et al.*, 1984). Other investigations concerning the mechanism of the shading effect were also discussed in Section 1.3.6.3 $^{\text{Ch. 2}}$.

Another contributing factor resulting in a reduced yield at 1.0 H may also have been attributed to increased wind speeds resulting from the large number of gaps in the windbreak profile. Rocheleau *et al.* (1988) noted that if the lower level of the windbreak was left open while the upper section was too dense, the result could cause serious damage to crops due to excessive turbulence. A combination of higher wind speeds and shading by the windbreak was therefore the likely cause of the low above-ground $^{\text{mass}}$ observed at 1.0 H.

A note of caution must be mentioned to these conclusions. Considering that SaS1 has been historically rotated with livestock on an annual basis, some compaction of the soil nearer the windbreak from camping livestock may have occurred over the years. Hawke and Gillingham (1996) from New Zealand also showed how enhanced pasture growth was due to nutrient transfer from camping livestock. They noted that where livestock were rotated with crops, it was possible that the higher yields nearer the windbreaks were not directly related to shelter but to unequal distributions of manure fertiliser.

3.4 Conclusions of microclimate variation at SaS1

3.4.1 Shelter effect

There was little possibility of a shelter effect at SaS1 due to the 4 m high gaps in the lower profile of the windbreak. The above-ground^{mass} fluctuations that occurred from 2.0 to 25.0 H were more likely due to very localised soil variations than to any wind speed variation.

3.4.2 Competition effect

Low yields at 1.0 H (compared to those at 2.0 H) were attributed to shading from the adjoining northern windbreak. Due to the consistent soils at 1.0 and 2.0 H, crops yields could be directly compared with each. Compared to the above-ground^{mass} at 2.0 H, those at 1.0 H were significantly reduced ($p < 0.05$) by an average of 44%. The highest above-ground^{mass} across the site was recorded at 2.0 H, hence the competition effect was restricted to 1.0 H from the windbreak. This magnitude and extent of above-ground competition at SaS1 was consistent with the observations observed on the southern side of the ViS1 and WoS3 windbreaks. The extent of below-ground competition was considered negligible, as soil moisture levels were not considered to be limiting during the winter growth period.

4 WOLSELEY SITE 1 (WoS1)

4.1 Method

4.1.1 Regional description

WoS1 was located 5 km south of Wolseley (longitude: 19°12′E, latitude: 33°26′S, altitude: 260 m) on the farm “La Plaisante” owned by three brothers - Anthony, Peter, and Nicolas Dicey. Plate 1.1 in Section 3.2 $^{\text{Ch. 1}}$ illustrates the location of WoS1 in the Western Cape Region. The farm was established in the late 1800's, and enterprises consisted of citrus, peach, and pear orchards, and some vineyards.

Table 2.4.1 shows the summarised long term and 1998 data collected from the DWAF weather station (conveniently located on the “La Plaisante” farm, 2 km east of the site). The average yearly long-term wind speed at Wolseley was 142 km / day. Average wind speeds were much more consistent and lower compared to the Saron area. This was somewhat surprising as the south-easterly winds are also reputed to be severe in the Wolseley region, although perhaps not as extreme as in the Saron region. The lower and more consistent wind speeds at the DWAF weather station at Wolseley were probably due to the poor location of the weather station, where houses and trees adjoining the southern side probably produced a shelter effect. Therefore, the wind speeds at this location were not considered to be maximum (fully exposed) wind speeds. However, the wind speed data provided information concerning seasonal variation of winds.

The average daily maximum temperature in this region was 30.4°C for the hottest months (January and also February) and the average daily minimum temperature for the coolest month (July) was 6.6°C. The site is in a temperate winter rainfall region, with June having the highest average monthly rainfall (102.1 mm), and January having the lowest average monthly rainfall (11.9 mm). Data for total evaporation and Relative Humidity (RH) are also included in Table 2.4.1.

Table 2.4.1 Long-term records and 1998 records of weather data recorded at the "La Plaisante" weather station near Wolseley.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Long term av. wind speed (km / day)	158.6	160.7	145.9	123.4	117.8	125.5	129.0	132.3	137.2	151.5	159.9	158.8
1998 av. wind speed (km / day)	47.4	73.6	56.2	28.5	51.4	29.0	105.5	106.4	127.4	129.0	133.8	144.5
1998 av. max. wind speed (km / day)	159.9	261.4	187.8	99.7	222.8	130.7	244.9	200.4	211.7	257.2	241.2	417.7
Long term av. daily max. temp. (°C)	30.4	30.4	28.5	24.6	20.6	17.6	17.0	17.6	20.2	23.4	26.5	28.8
Long term av. daily minimum temp. (°C)	15.7	16.0	14.7	12.1	9.3	7.4	6.6	7.0	8.6	10.7	12.8	14.6
1998 av. daily maximum temp. (°C)	30.0	32.1	28.4	25.9	20.3	18.3	16.9	19.1	20.8	24.5	25.7	29.3
1998 av. daily minimum temp. (°C)	14.7	17.9	14.8	12.3	9.2	7.1	6.4	6.6	7.8	9.6	12.0	15.3
Long term av. total rain (mm)	11.9	16.2	20.8	44.4	81.9	102.1	84.0	83.6	49.3	36.2	24.6	19.0
1998 total rain (mm)	33.0	0.0	3.0	22.6	220.4	58.9	80.0	30.4	14.4	21.2	70.5	64.7
Long term av. total evaporation (mm)	301.5	252.6	211.9	131.2	84.7	61.9	65.9	81.7	117.3	184.8	244.5	281.6
1998 total evaporation (mm)	270.0	251.0	209.0	132.1	65.8	50.9	56.5	78.4	113.4	159.7	199.5	238.5
Long term av. daily max. RH (%)	86.8	88.1	89.6	91.8	93.0	92.5	93.1	93.2	92.7	90.5	88.2	87.3
1998 av. daily max. RH (%)	84.6	86.8	87.7	88.2	92.0	94.2	93.0	91.7	90.2	90.1	90.3	90.0

4.1.2 Site description

An aerial view of WoS1 is illustrated in Plate 2.4.1, and a profile view of the southern windbreak is illustrated in Plate 1.5 in Section $3.2^{\text{Ch. 1}}$. This site had two parallel *C. cunninghamiana* windbreaks (average effective height (H) was 8.0 m) adjoining the north and south borders of a vacant block of land. The distance between the two windbreaks was 125.0 m. Therefore, the space between the two windbreaks was 15.6 H. The windbreaks were orientated in an east-west direction, hence were well orientated for prevailing south-easterly winds. The 3-year old windbreak was double-rowed and trees were spaced 1 m from each other in a non-staggered formation. Gaps were minimal along the profile of both windbreaks.

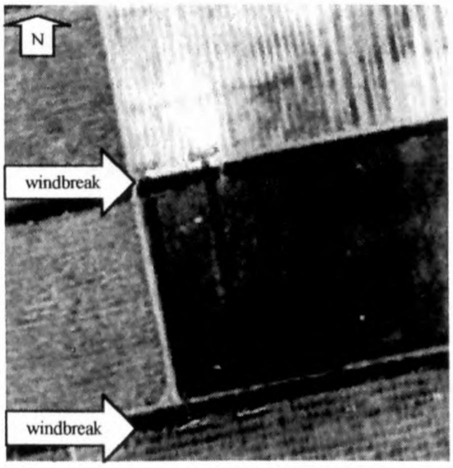

Plate 2.4.1 Aerial view of the WoS1 windbreak. Prevailing winds were south-easterly. Scale 1:4600

The width of the experimental site was 40.0 m. Access tracks were adjacent to both windbreaks, hence the experimental design could extend only as close as 6.0 m from each of the windbreaks. Each windbreak extended for approximately 1 km on either side of the site. Orchards existed on the other side of each of the windbreaks, thus preventing any measurements beyond the windbreak boundary. The area between the two windbreaks was cleared of vines (including stumps and root systems) in 1992, and was then planted with oats until 1996. The site then remained fallow for 2 years before orchards were established in June 1999.

Soil pits were excavated on 21 August 1998 at three points within the research site, each to a depth of 2.5 m. Each soil profile revealed a Dundee 1210 soil classification (Munsell Color Co., 1975):

1. An orthic A horizon at 0 to 30 cm depth, about 10% clay content, and a fine to medium sand grade.
2. A stratified alluvium material with signs of wetness (C1 and C2 horizon) at 30 and 120 cm depth, about 12% clay content, and a fine to medium sand grade.
3. A stratified alluvium material with signs of wetness (C3 horizon) at 120 to > 140 cm depth, about 3% clay content, and a medium to coarse sand grade.

4.1.3 Experimental design

The general shape of the design was a 40.0 m wide block extending 125.0 m (15.6 H) between the two windbreaks. Plate 2.4.2 illustrates the plan of WoS1 experimental design. Five replicates (each 8.0 m wide) were set perpendicular to the windbreak, each containing triticale (*Triticosecale* cultivar Rex) that is a hybrid between wheat (*Triticum aestivum*) and rye (*Secale cereale*). Samples of above-ground$^{\text{mass}}$ were harvested from each replicate at specific points from the southern windbreak. These points were designated at 8.0 to 10.0, 16.0 to 18.0, 24.0 to 26.0, 40.0 to 42.0, 56.0 to 58.0, 72.0 to 74.0, 88.0 to 90.0, and 112.0 to 114.0 m (1.0, 2.0, 3.0, 5.0, 7.0, 9.0, 11.0, and 14.0 H respectively) to the leeward side of the southern windbreak.

Samples of above-ground^{mass} were harvested from plots that were 1.0 m wide and extended for 2.0 m northwards from the designated distance from the southern windbreak. Sampling occurred from 20 to 30 December 1998 when the mature crop was four months old. Each harvested sample was bagged, oven-dried at 100°C, and weighed for above-ground^{mass}. Weeds were distributed uniformly across the site, but did not appear to compete with the wheat crop to a significant degree. Weeds were not included in the samples.

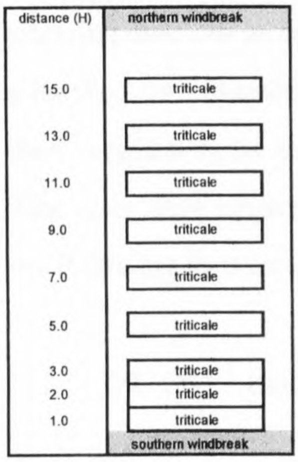

Plate 2.4.2 Plan of WoS1 experimental design.

4.1.4 Site preparation

The site was ploughed on 29 July 1998 and sprayed with 2 L / ha Roundup herbicide (glyphosate as the active ingredient, making up 360 g / L of the herbicide) on 19 August 1998. On 4 September 1998, triticale (400 kg / ha), 400 kg / ha superphosphate (10.5%), 100 kg / ha 2:3:2 (22%), and 100 kg / ha LAN (28%) was evenly sown throughout the site using a fertiliser "spreader" attached to the back of a tractor. Seed was ploughed into the soil immediately following sowing.

4.1.5 Wind speed and soil moisture measurements

The portable weather station was unavailable for use at WoS1 during 1998. To obtain information concerning soil moisture content (MC%) variation across the site, multiple gravimetric sampling commenced on 26 October 1998. The procedure was repeated on 6 November, 18 November, and finally on 2 December 1998. The first sampling took place in dry conditions, and the second sampling followed several days of heavy rainfall. The final two soil collections took place in increasingly hot and dry conditions.

Soil was sampled at 1.0, 2.0, 3.0, 5.0, 7.0, 9.0, 11.0, 13.0, and 14.0 H to the lee of the southern windbreak at each of the outer edges of the 8.0 m wide replicates. Soil samples were measured from soil cores taken at 15 to 20 cm below the soil surface. For each sampling date, 90 samples were collected. Sampled soil was immediately sealed tightly in a labelled tin. Weather during sampling was hot and dry. Each sealed tin was weighed, then weighed again following oven drying with lids loosened (at 100°C for 24 hours). Tins were then emptied and weighed. The following calculations were then made using the following formula:

$$\text{MC }(\%) = (\text{undried soil}^{\text{mass}} - \text{dried soil}^{\text{mass}}) / \text{dried soil}^{\text{mass}} \times 100$$

4.1.6 Windbreak porosity

Windbreak porosity was estimated using two photographs of 3 m x 3 m samples for each windbreak. Each image was scanned and then posturised by computer. The porosity was calculated using an image digitalisation programme that calculated the number of darker pixels compared to lighter pixels. The porosity of the two images from each windbreak was then averaged.

4.1.7 Statistical methods

Crop data and soil moisture data were analysed by ANOVA. Statistical analysis was done with SAS (SAS Institute Inc., 1985).

4.2 Results

4.2.1 Climatic and soil data

From the regional DWAF weather station records (Table 2.4.1 in Section 3.1.1 $^{\text{Ch. 3}}$, wind speeds near Wolseley were much lower and more constant compared with the other locations near Saron and Villiersorp. Although the south-easterly winds were reputably severe in the Wolseley region, the consistency of the average wind speeds throughout the year suggest that these prevailing winds are either not as numerous or not as sustained as the other sites studied in this project.

The presence of houses and large trees on the southern side of the DWAF weather station near Wolseley may be another reason for the lower recorded wind speeds. Average wind speeds were similar to long term records from July to December 1998, but below average for the earlier half of the year. Maximum average wind speeds were consistently low throughout the year, except in December 1998, when the average maximum wind speed almost doubled (rising from 241 km / day in November to 418 km / day in December 1998).

For 1998 only, the highest averaged daily maximum temperature in this region was recorded in February (32.1°C) and the lowest average daily minimum temperature was recorded in July (6.4°C). Rainfall was low during the first half of the growing period of the crop, with 14.4 and 21.2 mm in September and October 1998 respectively. Rainfall levels of 70.0 and 64.7 mm in November and December 1998 respectively provided more favourable conditions for the latter half of the growing period. Total evaporation and average daily RH during 1998 were consistent with long term records.

During sowing, the triticale crop seed was spread beyond the plot boundaries, resulting in a lower stocking rate than initially anticipated. However, a good cover of triticale throughout each plot occurred, eventually drying following grain maturation in mid-December. Weeds were distributed uniformly across the site, but did not appear to compete with the triticale crops to a significant degree.

Table 2.4.2 in Section $4.2.2^{\text{Ch. 3}}$ summarises the means of the above-ground$^{\text{mass}}$ and the means of the four samplings for soil moisture content, in relation to the distance to the lee of the southern windbreak. The average porosity of the southern WoS1 windbreak was calculated to be 37%.

4.2.2 Yield and soil moisture data

Table 2.4.2 Summary of the means* of above-ground^{mass} and the four samplings for soil moisture content, for various distances (H)** from the southern WoS1 windbreak.

distance (H)	above-ground^{mass} (g)	*MC (%) for 26 Oct.****	*MC (%) for 6 Nov.*	*MC (%) for 18 Nov.*	*MC (%) for 2 Dec.*
1	421.8_a	3.90_a	11.61_a	6.56_a	2.65_a
2	406.7_a	3.48_a	11.52_a	6.79_a	2.67_{ab}
3	491.6_a	3.95_a	11.52_a	7.52_a	3.45_a
5	284.0_a	-	10.50_{ab}	4.88_b	2.63_{ab}
7	425.0_a	2.12_{bc}	10.03_{abc}	4.16_{bc}	2.16_b
9	385.2_a	2.34_b	8.34_d	3.74_{bcd}	1.94_b
11	433.4_a	1.82_{bc}	8.15_d	3.51_{cd}	1.86_b
13	-	1.51_c	8.94_{dc}	3.17_{cd}	1.70_b
14	452.5_a	1.50_c	9.83_{bc}	2.81_d	1.63_b

* Means with the same subscript were not significantly different using the ANOVA method. Subscripts relate to respective columns only. No yield was assessed at 13.0 H.

** Effective tree height (H) was 8.0 m. Distances were located to the lee of the windbreak to prevailing winds.

*** No soil samples were collected at 5.0 H on 26 October.

There was no significant difference ($p > 0.05$) between leeward distance from the southern windbreak and above-ground^{mass}. Figure 2.4.1 illustrates the averaged variation of above-ground^{mass}, in relation to the southern WoS1 windbreak.

For the soil sampled on 6 November 1998, there was a significant decrease in soil moisture content ($p < 0.05$) due to leeward distance from the windbreak. For the soil sampled on 26 October and 18 November 1998 there was a significant decrease in soil moisture content ($p < 0.05$) due to leeward distance from the windbreak, but interaction between replicates and distance was also significant ($p < 0.05$). For the soil sampled on 2 December 1999, no significant relationship was found between leeward distance from and soil moisture. Figure 2.4.2 illustrates the averaged variation of soil moisture content, in relation to the southern WoS1 windbreak.

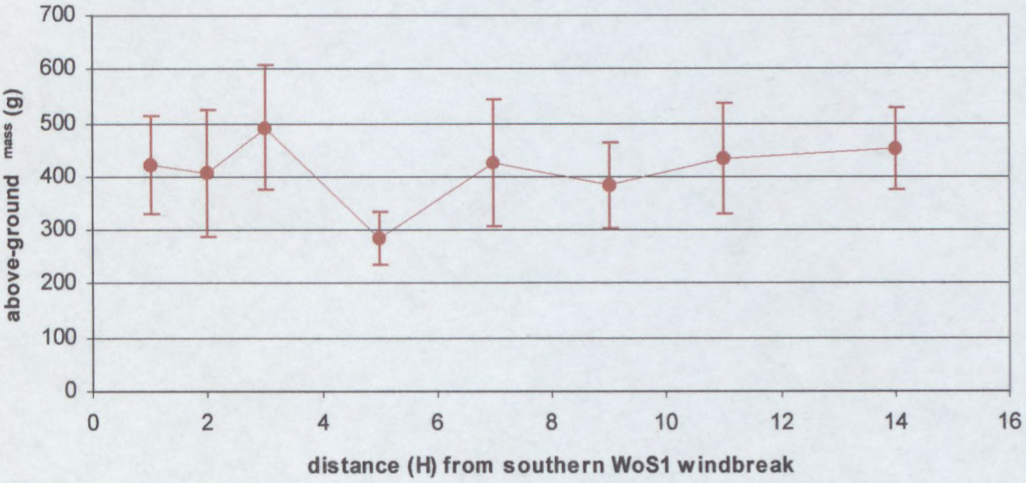

Figure 2.4.1 Averaged variation of above-ground$^{\text{mass}}$, in relation to the southern *C. cunninghamiana* windbreak at WoS1. Effective tree height (H) was 8.0 m. Error bars indicate the level of the 95% confidence interval for each treatment. Data points have been joined to enhance visual presentation.

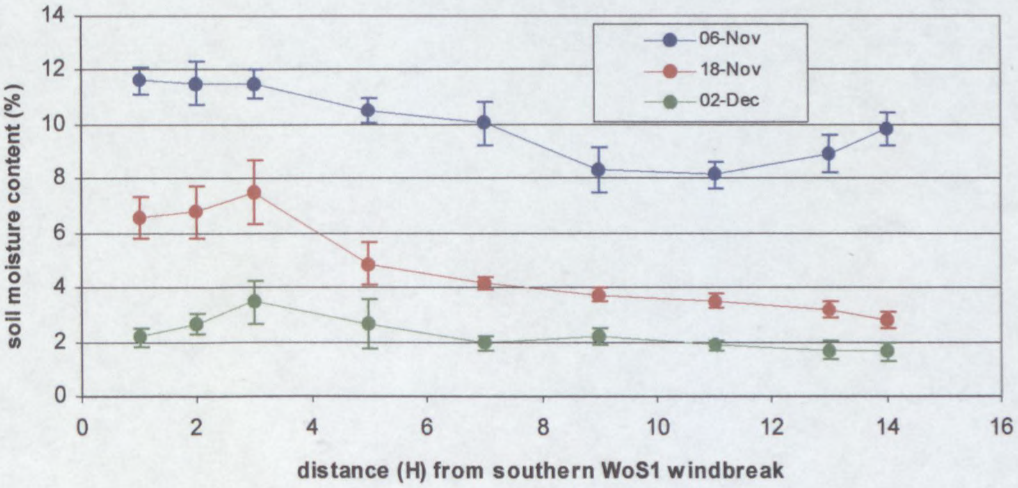

Figure 2.4.2 Averaged variation of soil moisture content (sampled on 6 November 1998, 18 November 1998, and 2 December 1998), in relation to the southern *C. cunninghamiana* windbreak at WoS1. Effective tree height (H) was 8.0 m. Data from the soil sampled on 26 October 1998 was excluded from Figure 4.3, as it was similar to the data from the soil sample on 2 December 1998. Error bars indicate the level of the 95% confidence interval for each treatment. Data points have been joined to enhance visual presentation.

4.3 Discussion

4.3.1 Shelter effect

The soil moisture data are summarized in Table 2.3.3 and illustrated in Figure 2.4.2 (Section 4.2.2 $^{\text{Ch. 3}}$). From the soils sampled on 26 October 1998, 6 November 1998, 18 November 1998, and 2 December 1998, a consistent and significant ($p < 0.05$) lowering of soil moisture content occurred with increasing distance from the southern windbreak. The consistent soil classifications from the excavated soil pits (Section 4.1.2 $^{\text{Ch. 3}}$) might have indicated that the variation of soil moisture was due to a shelter effect (or more specifically, a soil-moisture conservation effect) to the lee of the southern windbreak. The leeward extent of the maximum shelter effect was generally estimated to extend from 3.0 to 6.0 H (Cleugh and Hughes, 2000; Cleugh, 1998; Sun and Dickinson, 1997; Hodges and Brandle, 1996; Bird, 1988; Ujah and Adeoye, 1984).

The trend of soil moisture from the soil sampled on 26 October1998 initially suggested this potential shelter effect. The soil sampled on 6 November 1998 was collected immediately following heavy rains, so it represented the distribution of the near-field capacity levels across the site. Soil moisture variation was expected to be minimised, but the trend of a lowering of soil moisture content with increasing distance from the southern windbreak persisted, although at a predictably higher level. Therefore, soil moisture variation across the site was unlikely to have been the result of a shelter effect from the southern windbreak. The soils sampled on 18 November 1998 and 2 December 1998 indicated a gradual return of soil moisture levels to the earlier drier conditions observed for the soils sampled on 26 October1998.

As work at WoS1 progressed, it became increasingly clear that the trend of a lowering of soil moisture content with increasing distance from the southern windbreak was due to a slight physical depression in the southern section of the site. This depression is evident in Plate 4.1.1 (Section 4.1.2 $^{\text{Ch. 3}}$), extending from the right hand corner of the plate in a south-west direction. Therefore, despite a consistent soil type across the site, slight variation in elevation interacted with a potential soil moisture conservation effect.

Although variation of the above-ground$^{\text{mass}}$ was not significantly different ($p > 0.05$) at any distance from the windbreak, average above-ground$^{\text{mass}}$ was 7% higher at 3.0 H compared to 14.0 H. Figure 4.1 illustrates the averaged variation of above-ground$^{\text{mass}}$, in relation to the southern WoS1 windbreak.

The DWAF weather station located on the same farm was of little value as it was actually sheltered by houses and trees immediately located on the southern side. However, the 1998 wind speed data (Table 2.4.1 in Section 4.1.1$^{\text{Ch. 3}}$) did provide useful comparisons to long-term records. Compared to long-term records, maximum wind speeds were consistently low throughout the year. This might explain the insignificant crop shelter effect.

4.3.2 Competition effect

The trend described for the moisture content for the soil sampled on 6 November 1998 changed in one important way for the two following samplings on 18 November 1998 and 2 December 1998 (Table 2.4.2 and Figure 2.4.2 in Section 4.2.2$^{\text{Ch. 3}}$). Soil moisture levels at 1.0 H increasingly became lower, compared to the respective soil moisture levels at 3.0 H. This might indicate a competition effect at 1.0 H, attributed to the adjoining southern windbreak. On 6 November 1998, the difference between the soil moisture content at 1.0 and 3.0 H was negligible (averaging 11.6 and 11.5% respectively). This indicated that soils at these two locations had similar near-field capacities following heavy rain. On 18 November 1998, the average soil moisture content was 6.6 and 7.5% at 1.0 and 3.0 H respectively. On 2 December 1998, the average soil moisture content 1.0 and 3.0 H diverged further, to 2.2 and 3.5% respectively. Although not significant ($p > 0.05$), this divergence of soil moisture at 1.0 and 3.0 H suggested a possible intensification of soil moisture uptake by the adjoining southern windbreak. The soil moisture content at 2.0 H was intermediate to those at 1.0 and 3.0 H. Therefore, the soil moisture depletion extended to 2.0 H, although in a reduced capacity compared to 1.0 H.

Although variation of the above-ground$^{\text{mass}}$ was not significantly different ($p > 0.05$) at any distance from the windbreak, average above-ground$^{\text{mass}}$ was 14% higher at 3.0 H compared to 1.0 H. This further indicated a potential below-ground competition effect occurring at 1.0 H, compared to 3.0 H. Windbreaks generally caused a reduction in crop growth up to 1.5 to 2.0 H from the trees (Kowalchuk and De Jong, 1995; Puri *et al.*, 1992; Baldwin, 1988; Lyles *et al.*, 1984). Further investigations concerning the extent of competition were discussed in Section 1.3.6.3$^{\text{Ch. 2}}$.

No competition effect was observed on the northern sides of the ViS1 and WoS3 windbreaks respectively described in the last paragraph in Section 1.3.6.2 and the last paragraph of Section 2.3.2$^{\text{Ch. 3}}$. This perhaps indicates that below-ground competition might only occur when the majority of the crop's growing period occurs during dry conditions, as in the case at WoS1. The crops growing earlier in the growing season at ViS1 and WoS3 had sufficient soil moisture to avoid competition with the adjoining windbreaks.

Drought stress increases competition for moisture (Sanchez, 1995; Banzhaf *et al.*, 1992). Yield responses to shelter were actually higher in dry than in wet years, but the level of competition near the trees was more pronounced (Kowalchuk and De Jong, 1995; and Kort, 1988). Summarising Russian investigations, noted that in wet years hay yield increases were 10 to 20%, and in dry years the benefit increased to 40 to 100%. When water was more abundant, the competition effect was smaller and the zone of improved crop growth was absent (Haigh, 1994). From field experiments conducted in the arid savannah zone of Sudan, Ujah and Adeoye (1984) found that *E. camaldulensis* windbreaks had little influence on the millet crops during the rainy season. However, immediately following the last rains, moisture depletion (due to accelerated evaporation) was more rapid on the unprotected fields compared to the sheltered leeward fields.

Unlike the sites at ViS1, WoS3, and SaS1, the northern WoS1 did not have a crop strip adjoining the northern windbreak. Therefore no shading effect by the northern windbreak on the crop was possible.

4.3.3 Crop species

The insignificant variation of above-ground^{mass} ($p > 0.05$) across the site might be attributed to another factor, as well as the elevation effect. A further potential interaction was the crop species. At WoS1, triticale was chosen because of its greater tolerance to drought conditions than most other cereals. As the crop was to be planted as late as September, this attribute was vital if the crop was to survive to maturity in the Western Cape Region. Normally, most cereals in this region are sown in April or May, and begin to mature in September or October. Therefore, the planting of any cereal so late in the year was a considerable risk; but the risk was reduced by the selection of a more drought tolerant crop species. Fortunately, an unseasonably high level of rain fell in November, thus ensuring maturation.

As well as being drought tolerant, triticale is one of the more wind tolerant crop species. This tolerance to wind and drought tolerance is well known to many farmers in the north Western Cape, who in fact use strips of triticale as windbreaks for more wind sensitive crops. This may explain the absence of observable physical damage and also the absence of any significant variation of above-ground^{mass} across the site.

Crops vary in their tolerance to wind and abrasion by wind-blown soil. There were four categories of crops listed by Finch (1988):

1. tolerant crops (grain and forage crops),
2. moderately tolerant crops (corn and sorghum crops),
3. low tolerance crops (orchard and vineyard crops), and
4. very low tolerance crops (vegetable crops).

Although tolerant crops may require only a minimum of wind protection to prevent physical damage, the benefits of shelter to these crops in terms of yield can be significant. As the tolerance level decreases, the need for more extensive shelter networks becomes increasingly important.

Also, vegetable crops required a greater wind speed reduction than other agricultural crops (Zhang *et al.*, 1995). Sand blasting reduced seedling survival, early growth, and yield of vegetable crops in wind tunnel experiments (Armburst, 1984; Downes *et al.*, 1977). However, cowpea was observed to be much more tolerant to the effects of sandblasting, due to rapid new growth after physical injury.

Although there are numerous reports of significant differences in response to windbreaks between crop species, little information is available to explain these differences. There is a clear need for clarifying the effect of shelter at critical development stages for each crop species (Nuberg, 1998; Van Gardingen and Grace, 1991). Some plant species might have a higher water-use efficiency than others because of a higher mesophyll conductance relative to the conductance through the leaf (Brown and Simmons, 1979).

4.4 Conclusions of microclimate variation at WoS1

4.4.1 Shelter effect

A soil moisture conservation effect by the southern WoS1 windbreak was not indicated. The generally significant trend ($p < 0.05$) of a lowering of soil moisture content with increasing distance from the southern windbreak was due to a slight physical depression in the southern section of the site. Above-ground$^{\text{mass}}$ was not significantly different ($p > 0.05$) at any distance from the windbreak. Triticale was not a good choice of crop species for windbreak research as this species is relatively wind tolerant.

4.4.2 Competition effect

As conditions became drier, average soil moisture levels at 1.0 and 3.0 H diverged from a negligible level on 6 November 1998 to a 22% lower level ($p > 0.05$) at 1.0 H (compared to 3.0 H) on 2 December 1998. This indicated a possible intensification of soil moisture uptake by the adjoining southern windbreak. The average above-ground$^{\text{mass}}$ was 14% higher ($p > 0.05$) at 3.0 H compared to 1.0 H, further indicating a potential competition effect. The soil moisture content at 2.0 H was intermediate to those at 1.0 and 3.0 H. Therefore, the soil moisture depletion extended to 2.0 H, although in a reduced capacity compared to 1.0 H. No competition effect was observed on the northern sides of the ViS1 and WoS3 windbreaks. This perhaps indicated an increased potential for below-ground competition for crops growing in drier conditions, as in the case at WoS1. The crops growing earlier in the growing season at ViS1 and WoS3 had sufficient soil moisture to avoid competition with the adjoining windbreaks.

5 WOLSELEY SITE 2 (WoS2)

5.1 Method

5.1.1 Regional description

WoS2 was located 500 m northwards of WoS1. The regional description described for WoS1 in Section 4.1.1$^{\text{Ch. 3}}$ was therefore applicable for WoS2.

5.1.2 Site description

An aerial view of WoS2 is shown in Plate 2.5.1, located 500 m northwest of WoS1. A profile view of the site (from the southern boundary) is shown in Plate 1.6 in Section 3.2$^{\text{Ch. 1}}$. WoS2 was comprised of a sheltered orchard of pears (*Pyrus communis* L. variety Rosemary) and a nearby section that was not sheltered. The sheltered section of the orchard had a *C. cunninghamiana* windbreak with an average effective height (H) of 12.0 m extending along the southern boundary. The unsheltered section of the orchard, which was located 60 m to the east of the sheltered section, had no windbreak on the southern boundary. It was hoped that differences in yield between the sheltered and unsheltered zones (treatments) would be detected. The 40.0 m wide sheltered zone was located 30.0 m westwards of the eastern edge of the windbreak of the southern boundary. The 40.0 m wide unsheltered zone was located 30.0 m further eastwards of the eastern edge of the windbreak on the southern boundary.

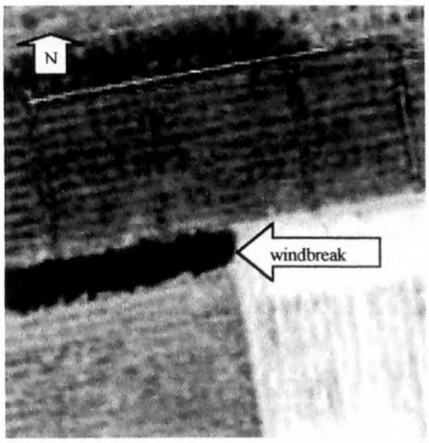

Plate 2.5.1 Aerial view of the WoS2 windbreak. Prevailing winds were south-easterly. Scale 1:3000.

The orchard extended 61.0 m (5.1 H) to the leeward side of the windbreak. The windbreak was orientated in an east-west direction, and therefore well orientated for prevailing south-easterly winds. The 4-year old windbreak was double-rowed and the trees were spaced 1.0 m from each other in a non-staggered pattern. Gaps were minimal along the windbreak profile.

The 10-year old pear orchard was pruned yearly to an average height of 3.5 m. Orchard trees in each row were spaced 2.0 m apart in the row, and rows were spaced approximately 4.6 m apart. The orchard had been treated (fertilised, sprayed, and pruned) uniformly throughout its history. The windbreak extended for approximately 700 m further westwards of the site. Orchards surrounded the site, thus preventing any measurements beyond the described boundaries. Soil pits were not excavated at this site as the Dundee 1210 soil classification (Munsell Color Co., 1975) described for WoS1 in the last paragraph of Section 4.4.1 $^{\text{Ch. 3}}$ was known to be consistent in this region (Freddie Ellis, personal communication).

5.1.3 Experimental design

Plate 2.5.2 illustrates the plan of the WoS2 experimental design. Orchard rows ran parallel to the southern boundary. Five replicates in each treatment extended perpendicular from the southern boundary to the northern boundary. Therefore, each replicate of each treatment was 61.0 m in length and 8.0 m in width. This width was chosen so that four trees in each row were included in the respective replicate.

From each replicate, pears from rows 1, 2, 3, 5, 7, 9, and 11 were collected in 0.5 m^3 containers. These rows were spaced at 5.0, 10.0, 15.0, 24.0, 33.0. 42.0, 51.0, and 63.0 m (0.4, 0.8, 1.3, 2.0, 2.8, 3.5, 4.3, and 5.1 H respectively). Rapid collection of pears was made possible with the aid of the farm owners and 15 of their fruit pickers. Pear picking was completed in six hours, on 14 January 1999.

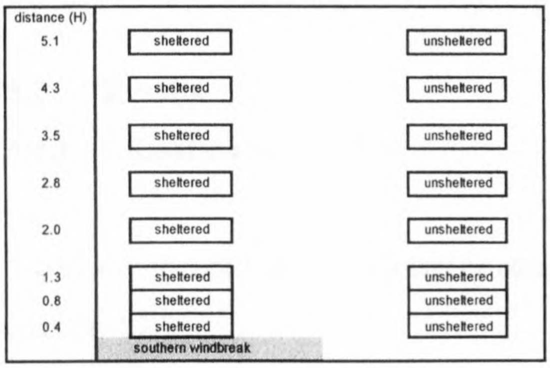

Plate 2.5.2 Plan of the WoS2 experimental design.

5.1.4 Site preparation

Site preparation was not necessary. Boundaries of the replicates of each treatment were clearly marked with tape. Fruit pickers were informed of the aims of the experiment and were closely supervised.

5.1.5 Wind speed and soil moisture measurements

No measurements of wind speed or soil moisture variation were made. The portable weather station was unavailable for use at WoS2 during 1998.

5.1.6 Windbreak porosity

Windbreak porosity was estimated using two photographs of 3.0 m x 3.0 m samples for each windbreak. Each image was scanned and then posturised by computer. The porosity was calculated using an image digitalisation programme that calculated the number of darker pixels compared to lighter pixels. The porosity of the two images from each windbreak was then averaged.

5.1.7 Statistical methods

Crop yield was analysed by ANOVA. Statistical analysis was done with SAS (SAS Institute Inc., 1985).

5.2 Results

5.2.1 Climatic and soil data

WoS2 experienced the same weather conditions that were described for the for WoS1 in Section 4.2.1 $^{\text{Ch. 3}}$.

5.2.2 Yield data

Table 2.5.1 summarises the means of pear $^{\text{volume}}$ for various distances from the southern WoS2 boundary; for sheltered and non-sheltered treatments. The average porosity of the southern WoS2 windbreak was calculated to be 27%.

Table 2.5.1 Summary of the means* of pear ^{volume} for various distances (H)** from the southern WoS2 boundary; for sheltered and non-sheltered treatments.

Distance (H)	*sheltered yield (0.5 m^3 boxes)*	*non-sheltered yield (0.5 m^3 boxes)*
0.4	6.3_a	6.4_c
0.8	7.8_a	9.4_b
1.3	6.2_a	6.2_c
2.0	5.5_a	8.0_c
2.8	4.8_a	8.0_c
3.5	5.8_a	6.8_c
4.3	6.8_a	11.2_a
5.1	8.2_a	8.2_{bc}

* Means with the same subscript were not significantly different using the ANOVA method. Subscripts relate to respective columns only

** Effective windbreak height (H) was 12.0 m. All distances were in relation to the southern boundary

Figure 2.5.1 illustrates the averaged variation of pear ^{volume} in relation to distances from the southern WoS2 boundary. For the sheltered treatment, distance to the lee of the southern boundary did not have a significant effect ($p < 0.05$) on pear volume (yield). For the non-sheltered treatment, distance from the southern boundary had a significant effect ($p < 0.05$) on yield. For all distances combined, there was no significant difference between treatments ($t > 0.05$). Yield at 0.8 H was found to be significantly higher for the unsheltered treatment compared to the sheltered treatment ($t < 0.05$). For all other distances, there was no significant difference between treatments ($t > 0.05$). For the non-sheltered treatment, the highest average yield (11.2 boxes) was recorded at 4.3 H to the lee of the southern boundary.

Due to the proximity of this site to WoS1, no soil analysis was undertaken. The lack of significant results was a further reason for not analysing the soil.

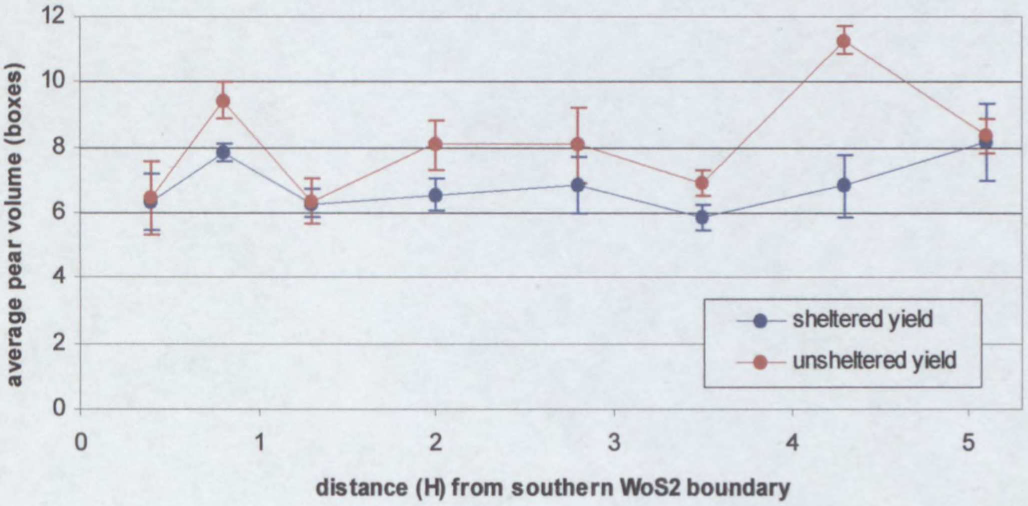

Figure 2.5.1 Averaged variation of pear volume in relation to distances from the southern WoS2 boundary. Effective windbreak height (H) was 12.0 m. Error bars indicate the level of the 95% confidence interval for each treatment. Data points have been joined to enhance visual presentation.

5.3 Discussion

The complete lack of any meaningful variation between treatments at WoS2 was another indication of the importance of crop species selection for the analysis of windbreak shelter effects, discussed earlier in Section 4.3.3 Ch. 2 for WoS1. Table 2.5.1 summarises the data and Figure 5.1 illustrates the averaged variation of pear volume (Section 5.2.2 Ch. 3).

The Rosemary cultivar at this site is considered to be one of the more sensitive pear cultivars, but this sensitivity was not revealed in the results. It was suspected that, due to an accumulation of unknown factors over a decade of growth, interaction was simply too high to observe a shelter effect, regardless of any level of replication in the experimental design. Relationships between individual orchard trees (competitive or beneficial) as well as variations of individual orchard tree pruning, fertilising, and irrigation were probably the greatest sources of interaction. Soil effects were assumed to be consistent, as evidenced from the WoS1 soil descriptions (Section 4.2.1 Ch. 2).

A minimal period of crop growth may therefore be important in the analysis of crop yield in relation to a windbreak. It may not be mere coincidence that the most conclusive results for this project were produced from 2-week old and 6-week old barley damage assessments at ViS1 (Section 1.3.1.1 and 1.3.1.2$^{\mathrm{Ch.}\ 3}$). Such short periods of analysis made it possible for the shelter effect to be revealed before other accumulating factors such as soil variations and nutrient variations began to significantly interact. Hence, the accumulation of interactions over a 10-year growing period, as in the case of the orchard trees at WoS2, would possibly mask shelter effects.

Perhaps an assessment of quality of pears might have been more appropriate than the assessment of the quantity of pears, as quality might have been more directly related to wind damage than quantity. Pears could have been individually rated into classes of damage, in much the same way as for the barley damage assessments at ViS1. However, with 20 fruit pickers involved in the experiment, technical accuracy of class assessment at WoS2 could have been impossible, and the collection of pears moved at such a rate that there was no time to consider individual pears. Also, interactions occurring for pear quality may have remained significant, although being less significant than the interactions that occurred for pear quantity. With these conclusions, the remaining project focused on annual crop species, and WoS2 was subsequently abandoned in 1999.

Being on the same farm, WoS2 experienced the same weather conditions as for WoS1. The consistently low maximum wind speeds recorded at the DWAF weather station (Section 4.1.1$^{\mathrm{Ch.}\ 3}$) may be a further reason for the failure of WoS2 to show significant variation due to wind speed. Average maximum wind speeds increased in December 1998, but this was unlikely to have affected yield quantity.

5.4 Conclusions of microclimate variation at WoS2

The complete lack of any meaningful variation between treatments at WoS2 was another indication of the importance of crop species selection for the analysis of windbreak shelter effects. It may not be mere coincidence that the most conclusive results for this project were produced from 2-week old and 6-week old barley damage assessments at ViS1. Such short periods of analysis made it possible for the shelter effect to be revealed before other accumulating factors such as soil variations and nutrient variations began to significantly interact. Hence, the accumulation of interactions over a 10-year growing period to the pear trees at WoS2 possibly masked the shelter effect.

6 APPENDIX

Plate A1.1 Barley damage at 2.0 H* to the lee of the northern ViS1 windbreak, on 11 July 1999

Plate A1.2 Severe barley damage at 13.7 H* to the lee of the northern ViS1 windbreak, on 11 July 1999

* Effective tree height (H) was 7.0 m at ViS1.

Plate A1.3 Potato morphology at 2.0 H* to the lee of the northern ViS1 windbreak, on 5 September 1999

Plate A1.4 Potato morphology at 13.7 H* to the lee of the northern ViS1 windbreak, on 5 September 1999

* Effective tree height (H) was 7.0 m at ViS1

Plate A2.1 Green barley at 3.0 H* to the lee of the southern WoS3 windbreak, on 20 October 1999

Plate A2.2 Dried barley at 11.0 H* to the lee of the southern WoS3 windbreak, on 20 October 1999

* Effective tree height (H) was 7.0 m at WoS3.

7 REFERENCES

Abel N. *et al.* (1997) Agroforestry Design Principles. RIRDC Publication. In: Cleugh HA. (1998) Effects of windbreaks on airflow, microclimates and crop yields. Agrofor. Syst. 41: 55 - 84.

Armburst DV. (1984) Wind and sandblast injury to field crops: Effect of plant age. Agron. J. 76: 991 - 993.

Baldwin CS. (1988) The influence of field windbreaks on vegetable and speciality crops. Agric. Ecosyst. Environ. 22 / 23: 191 - 204

Banzhaf J., Leihner DE., Buerkert A. and Serafini PG. (1992) Soil tillage and windbreak effects on millet and cowpea: 1. Wind speed, evaporation and wind erosion. Agron. J. 84: 1056 – 1060.

Bicknell D. (1991) The role of trees in providing shelter and controlling erosion in the dry temperate and semi - arid southern agricultural areas of Western Australia. Proc. of a national conference in Albury: The Role of Trees in Sustainable Agriculture, pp. 21 - 39. Publ. National Agroforestry Working Group in conjunction with the Bureau of Rural Resources, Dept. Primary Industries and Energy, Canberra. In: Bird PR., Bicknell D., Bulman PA., Burke SJA., Leys JF., Parker JN., Van Der Sommen FJ. and Voller P. (1992) The role of shelter in Australia for protecting soils, plants and livestock. Agrofor. Syst. 20: 59 - 86.

Biddington NL. (1985) A review of mechanically induced stress in plants. Scientific Hort. 36: 12 - 20. In: Hodges L. and Brandle JR. (1996) Windbreaks: an important component in a plasticulture system. Hort. Technology 6: 177 - 181.

Bird PR. (1998) Tree windbreaks and shelter benefits to pasture in temperate grazing systems. Agrofor. Syst. 41: 35 - 54.

Bird PR., Bicknell D., Bulman PA., Burke SJA., Leys JF., Parker JN., Van Der Sommen FJ. and Voller P. (1992) The role of shelter in Australia for protecting soils, plants and livestock. Agrofor. Syst. 20: 59 - 86.

Bird PR. (1988) Financial gains of trees on farms through shelter. Proc. Internat. Forestry Conf. For the Australian Bicentary 1988. Aust. Forest Development Institute, Vol 2. In: Bird PR. (1998) Tree windbreaks and shelter benefits to pasture in temperate grazing systems. Agrofor. Syst. 41: 35 - 54.

Brown R. and Simmons R. (1979) Photosynthesis of grass species differing in carbon - dioxide fixation pathways: I. Water use efficiency. Crop Sci. 19: 375 - 379. In: Davis JE. and Norman JM. (1988) Effects of shelter on plant water use. Agric. Ecosyst. Environ. 22 / 23: 393 - 402.

Cleugh HA. and Hughes DE. (2000) The impact of shelter on crop microclimates: a synthesis of results from wind tunnel and field experiments. Unpublished.

Cleugh HA. (1998) Effects of windbreaks on airflow, microclimates and crop yields. Agrofor. Syst. 41: 55 - 84.

Cleugh HA., Miller JM. and Bohm M. (1998) Direct Mechanical effects of wind on crops. Agrofor. Syst. 41: 83 - 112.

Dickey GL. (1988) Crop water use and water conservation benefits from windbreaks. Agric. Ecosyst. Environ. 22 / 23: 381 - 392.

Downes J., Fryrear D., Wilson R. and Sabota C. (1977) Influence of wind erosion on growing plants. TRANS. ASAE 20: 885 - 889. In: Leihner D., Buerkert A., Banzhaf J. and Serafini P. (1993) Soil tillage and windbreak effects on millet and cowpea: 2. Dry matter and grain yield. Agron. J. 85: 400 - 405.

Eicker R., Viljoen GK. and Myburgh J. (1986) Efficiency of pine windbreaks for protecting apple orchards. Deciduous Fruit Grower, January, pp. 15 - 20.

Finch SJ. (1988) Field windbreaks: design criteria. Agric. Ecosyst. Environ. 22 / 23: 215 - 228.

Grace J. (1988) Plant response to wind. Agric. Ecosyst. Environ. 22 / 23: 71 - 88.

Grace J. and Russell G. (1982) The effect of wind and a reduced supply of water on the growth and water relations of *Festuca arundinacea*. Ann. Bot. 49: 217 - 225. In: Cleugh HA., Miller JM. and Bohm M. (1998) Direct mechanical effects of wind on crops. Agrofor. Syst. 41: 83 - 112.

Haigh H. (1994) Farm forestry. In: Forestry Handbook. Van der Sijde HA. (ed.) pp. 828 - 840.

Hawke M. and Gillingham A. (1996) Nutrient transfer by livestosck adjacent to managed and unmanaged shelterbelts. NZ Tree Grower 17: 35 - 37. In: Bird PR. (1998) Tree windbreaks and shelter benefits to pasture in temperate grazing systems. Agrofor. Syst. 41: 35 - 54.

Hodges L. and Brandle JR. (1996) Windbreaks: an important component in a plasticulture system. Hort. Technology 6: 177 - 181.

Howard SB., Ong CK., Black CR. and Khan AAH. (1997) Using sap flow gauges to quantify water uptake by tree roots from beneath the crop rooting zone in agroforestry systems. Agrofor. Syst. 35: 15 - 29.

Hough and Cooper (1988) The effects of shelter for cereal crops in an exposed area of Cleveland, NE England. Soil Use and Management 4 (1): 19 - 22. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Khan GS. and Ehrenreich JH. (1994) Effect of increasing distance from *Acacia nilotica* trees on wheat yield. Agrofor. Syst. 25: 23 - 29.

Kort J. (1988) The influence of field windbreaks on field and forage crops. Agric. Ecosyst. Environ. 22 / 23: 165 - 190

Kowalchuk TE. and De Jong E. (1995) Shelterbelts and their effect on crop yield. Can. J. Soil Sci. 75: 543 - 550.

Lyles L., Tatarko J. and Dickerson JD. (1984) Windbreak effects on soil water and wheat yield. Trans ASAE 20: 69 - 72. In: Sun D. and Dickenson GR. (1994) A case study of shelterbelt effect on potato (*Solanum tuberosum*) yield on the Atherton Tablelands in tropical north Australia. Agrofor. Syst. 25: 141 - 151.

Malik RS. and Sharma SK. (1990) Moisture extraction and crop yield as a function of distance from a row of *Eucalyptus tereticornis*. Agrofor. Syst. 12: 187 - 195.

Marshall JK. (1967) The effect of shelter on the productivity of grasslands and field crops. Field Crop Abstracts 20: 1 - 14. In: Bird PR. (1998) Tree windbreaks and shelter benefits to pasture in temperate grazing systems. Agrofor. Syst. 41: 35 - 54.

Mayus M., Van Keulen H. and Stroosnijder L. (1999a) A model of tree - crop competition for windbreak systems in the Sahel: description and evaluation. Agrofor. Syst. 43: 183 – 201.

Mayus M., Van Keulen H. and Stroosnijder L. (1999b). Analysis for dry and wet years with the WIMISA model of tree / crop competition for windbreak systems in the Sahal. Agrofor. Syst. 43: 203 – 215.

Munsell Color Co. (1975) Munsell Soil Color Charts. Macbeth Div. Kollmorgen Corp. Maryland, USA.

Myburgh J. and Viljoen GK. (1979) Protection of deciduous fruit trees against wind. The Deciduous Fruit Grower, March. pp. 72 - 78.

Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Ong CK., Black CR., Marshall FM. and Corlett JE. (1996) Principles of resource capture and utilisation of light and water. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Pretzechel M., Bohme G. and Krause H. (1991) Effects of shelterbelts on crop yield. Feldwirtschaft 32(5): 229 - 231. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Puri S. and Bangarwa KS. (1992) Effects of tree yield of irrigated wheat crops in semi - arid regions. Agrofor. Syst. 20: 229 - 241.

Rocheleau D., Weber F. and Field-Juma A. (1988) Agroforestry in dryland Africa. ICRAF. Nairobi, Kenya, 311 pp.

Russell G. and Grace J. (1978b) The effect of windspeed on the growth of grasses. J. App. Eco. 16: 319 - 330. In: Cleugh HA., Miller JM. and Bohm M. (1998) Direct Mechanical effects of wind on crops. Agrofor. Syst. 41: 83 - 112.

Sanchez PA. (1995) Science in agroforestry. Agrofor. Syst. 30: 5 - 55.

SAS Institute Inc. (1985) SAS Users Guide: Basic, Edition 5. Cary N.: SAS Institute Inc.

Smika DE. and Shawcroft RW. (1980) Preliminary study using a wind tunnel to determine the effect of hot wind on a wheat crop. Field Crops Research 3: 129 - 135. In: Cleugh HA., Miller JM. and Bohm M. (1998) Direct Mechanical effects of wind on crops. Agrofor. Syst. 41: 83 - 112.

Song ZM., Meng P., Zhang H., Lu G., Zhou H., Hong S., Liu Y. and Zhang T. (1987) A study on the effects of windbreaks on meteorological factors and wheat yield in Heilonggang reaches. In: Zhang H., Brandle JR., Meyer GE. and Hodges L. (1995) The relationship between open windspeed and windspeed reduction in shelter. Agrofor. Syst. 32: 297 - 311.

Sun D. and Dickinson GR. (1997) Early growth of six native Australian tree species in windbreaks and their effect on potato growth in tropical northern Australia. For. Eco. Man. 95: 21 - 34.

Sun D. and Dickinson GR. (1994) A case study of shelterbelt effect on potato (*Solanum tuberosum*) yield on the Atherton Tablelands in tropical north Australia. Agrofor. Syst. 25: 141 - 151

Tibke G. (1988) Basic principles of wind erosion. Agric. Ecosyst. Environ. 22 / 23: 103 - 122.

Ujah JE. and Adeoye KB. (1984). Effects of shelterbelts in the Sudan savanna zone of Nigeria on microclimate and yield of millet. Agric. For. Meteorol. 33: 99 - 107. In: Ritchie KA. (1988) Shelterbelt plantings in semi-arid areas. Agric. Ecosyst. Environ. 22 / 23: 425 - 440.

Van Gardingen PR. and Grace J. (1991) Plants and wind. Adv. Bot. Rese. 18: 189 - 253. In: Hodges L. and Brandle JR. (1996) Windbreaks: an important component in a plasticulturesystem. Hort Technology 6: 177 - 181.

Woodruff NP., Lyles L., Siddoway L. and Fryrear DW. (1972) How to control wind erosion. Agric Inf. Bull. No. 354, USDA - ARS, Washington DC, 22 pp. In: Cleugh HA., Miller JM. and Bohm M. (1998) Direct Mechanical effects of wind on crops. Agrofor. Syst. 41: 83 - 112.

Yunasa IAM., Mead DJ., Lucas RJ. and Pollock KM. (1995) Process studies in a *Pinus radiata*-pasture agroforestry system in a subhumid temperature environment: 2. Analysis of dry matter yields in the third year. Agrofor. Syst. 32: 185 - 204.

Zhang H., Brandle JR., Meyer GE. and Hodges L. (1995) A model to evaluate windbreak protection efficiency. Agrofor. Syst. 29: 191 - 200.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this chapter was to conclude the effect of the windbreaks at each of the five project sites, followed by recommendations of windbreak management to optimise the potential benefits of windbreaks on farms in the Western Cape Region of South Africa.

1 EFFECT OF WINDBREAK SHELTER AT EACH PROJECT SITE

1.1 General shelter benefits

The windbreak species near Wolseley (WoS1 and WoS3) was *Casuarina cunninghamiana*. The windbreak species near Saron (SaS1) was *Eucalyptus cladocalyx*, and the windbreak species near Villiersdorp (ViS1) was *Pinus radiata*. The microclimate variation discussed in Chapter 2 and the crop yield variation discussed in Chapter 3 indicated significant shelter benefits by windbreaks in the Western Cape Region of South Africa. The ViS1 windbreak provided significant shelter from northerly winds in winter/early spring 1999, and WoS3 provided significant shelter from southerly winds in late spring 1999. WoS1 indicated a soil-moisture conservation effect from southerly winds in late spring 1998. The shelter effect at SaS2 due to excessive windbreak porosity at this site.

The portable weather station data indicated a clear beneficial shelter effect on the microclimate at ViS1 and WoS3. The shelter effect was best illustrated by the consistently reduced wind speeds in the leeward sheltered zone of each site and for each sampling period. To improve the correlation of the shelter effect, mild southerly winds at ViS1 (contaminating data comprising 27% of the total data recorded at ViS1) and mild northerly winds at WoS3 (contaminating data comprising 28% of the total data recorded at WoS3) were excluded for the prediction equations of the shelter effect at each site. The generally consistent reductions of the shelter effect at ViS1 and WoS3 by these contaminating (non-prevailing) winds suggested the requirement of a series of parallel windbreaks at ViS1 to provide maximum shelter from both northerly winds and southerly winds.

1.1.1 Shelter benefit at ViS1

Compared to the more exposed wind speeds at 1.0 H to the windward side, wind speeds at ViS1 were reduced by 32% at 3.0 H for the sampling period from 15 June to 24 July 1999. Compared to 11.0 H, wind speeds at ViS1 were reduced by 47% at 3.0 H for the second sampling period from 24 July to 14 September 1999. The addition of an extra wind sensor at 1.0 H indicated a similar wind speed reduction to 3.0 H. With r^2 values above 93%, accurate linear prediction equations were produced.

The 2-week damage assessment indicated that damage was absent from 1.0 H to 5.1 H, intermediate at 7.3 and 11.1 H (averaging 7 and 9% damage respectively), and significantly highest ($X < 0.05$) at 13.7 H (by an average of 25%). The 6-week damage assessment indicated the severe damage was absent from 1.0 to 7.3 H and increasingly prevalent from 11.1 to 13.7 H (by an average of 35 and 98% respectively). The data from the damage assessments had little potential to interact with soil variations, and subsequently variation of crop damage was solely attributed to the shelter effect.

For ViS1, similar soils at 1.7 and 13.7 H suggested that any difference in yield between these locations was attributed to different wind speeds. Compared to 2.4 H, the absence of the shelter effect at 13.7 H resulted in a significantly reduced ($p < 0.05$) head production and transformed proportion of total head^{mass} from above-ground^{mass} (by an average of 88 and 63% respectively). Despite not being significant ($p > 0.05$), total head^{mass}, above-ground^{mass}, and leaf and stem^{mass} showed similar trends. The absence of the shelter effect at 13.7 H resulted in a reduced total head^{mass}, above-ground^{mass}, and leaf and stem^{mass}, compared to that at 2.4 H (by an average of 87, 42, and 31% respectively). The increase of yields at 13.7 H for above-ground^{mass} and leaf and stem^{mass} (compared to those at 11.1 H) suggested that vegetative production was influenced more by soil fertility than by wind speed. However, the reduced yields at 13.7 H for total head^{mass}, average head$^{\text{mass}}$, proportion of head$^{\text{mass}}$ from total$^{\text{mass}}$, and grain head number suggests that grain production (or grain initiation) was influenced by wind speed more than any soil effect.

Compared to 2.4 H, the absence of the shelter effect at 13.7 H resulted in a significantly reduced ($p < 0.05$) potato tuber$^{\text{mass}}$ (by an average of 25%), potato above-ground$^{\text{mass}}$ (40%), total tuber number of (34%), and small tuber number (44%). In contrast, the absence of the shelter effect at 13.7 H resulted in a insignificant reduction ($p < 0.05$) in large tuber number, relative to 2.4 H. This may indicate that an absence of a shelter effect caused potato plants to invest resources into fewer but larger potatoes, due to inhibition of tuber initiation by the absence of a shelter effect.

At 13.7 H only, leeward potato morphology (south : north stem ratio) indicated a significantly higher stem length ($p < 0.05$) on the southern side of each potato plant, compared to the respective northern sides of each potato plant. This may have been due to disproportionate tissue damage to the windward section of each plant, or disproportionate tissue growth on the leeward section of each plant. Compared to 2.4 H, the absence of the shelter effect at 13.7 H resulted in a significantly increased ($p < 0.05$) south : north stem ratio (by an average of 22%), and a significantly reduced ($p < 0.05$) north stem length (32%) and south stem length of (14%), relative to 2.4 H. Therefore, winds reduced stem length on both sides of each plant, but affected the north side more than the south side.

Barley yield differences between 1.0 and 13.7 H were not significantly different ($p > 0.05$), indicating that the effect of unsheltered wind speeds was similar to the effect from shading. Crop yields at 1.0 and 13.7 H could be directly compared, as the soils at these locations were similar. Potato yield differences between 1.0 and 13.7 H were also not significantly different ($p > 0.05$). An exception to this was for the large potato tuber number, which was significantly higher ($p < 0.05$) at 13.7 H, compared to 1.0 H. This suggested that large tuber production was reduced more by the effect from competition than by the effect of unsheltered wind speeds.

1.1.2 Shelter benefit at WoS3

Despite the late occurrence of strong southerly winds, the initial sampling period at WoS3 indicated that wind speeds at 11.0 H were reduced by 63 and 56% at 3.0 and 1.0 H respectively. Caution was necessary concerning the linear prediction equations due to the poor correlations for 3.0 and 1.0 H (r^2 was 72 and 85% respectively) compared to 11.0 H. Turbulence immediately behind the WoS3 windbreak might have been responsible for the slightly reduced shelter effect at 1.0 H, compared to 3.0 H at higher exposed wind speeds. Severe south-easterly winds in the second sampling period greatly improved the overall shelter effect, compared to the previous sampling period. Notably, the average hourly wind speed at 3.0 H dropped from 0.9 m / s in the previous sampling period at WoS3 to 0.8 m / s, despite the sharp increase in exposed wind speeds. Wind speeds at 11.0 H were reduced by 73 and 32% at 3.0 and 7.0 H respectively. With r^2 values above 94%, accurate linear prediction equations were developed.

For WoS3, the general decrease in yields from 3.0 to 11.0 H might have suggested a pronounced response to a decrease in the shelter effect in a leeward direction from the windbreak. However, the recovery of the high yields at 15.0 and 17.0 H suggested that reduced yields at 7.0 and 11.0 H were attributed more to the effect of soil variation than to wind speed variation. The occurrence of severe south-easterly winds was too late to affect vegetative growth of the barley crop at WoS3. However, the last stages of growth were potentially affected. Therefore, the best indication of a possible shelter effect at WoS3 was from the variation of the sub-sample^{mass} of 100 grains, where the yield was significantly higher ($p > 0.05$) at 2.0 H, compared to that at 17.0 H. The similar soils at 2.0 and 17.0 H suggested that any difference in yield between these locations was attributed to different wind speeds.

Compared to 17.0 H, the sub-sampled^{mass} of 100 grains was significantly higher ($p < 0.05$) at 2.0 H. Sub-sampled^{mass} of 100 grains increased from 2.09 g at 17.0 H to 2.63 g at 2.0 H, a 21% increase attributed to the shelter effect at WoS3. Despite a more productive soil at 15.0 H compared to that at 2.0 H, the sub-sampled^{mass} of 100 grains was still significantly higher ($p < 0.05$) at 2.0 H. Sub-sampled$^{\text{mass}}$ of 100 grains increased from 2.27 g at 15.0 H to 2.63 g at 2.0 H, a 14% increase attributed to the shelter effect overcoming the soil effect. Compared to 2.0 H, yields at 17.0 H were not significantly different ($p > 0.05$) for leaf and stem$^{\text{mass}}$, grain$^{\text{mass}}$, total$^{\text{mass}}$, and the proportion of grain$^{\text{mass}}$ from total$^{\text{mass}}$.

1.2 Extent of shelter at all sites

The characteristically severe winds in the Western Cape Region restricted the extent of shelter to a conservative level. The reduction of the effectiveness of the shelter effect due to contaminating winds (opposite in direction to the prevailing winds) at 1.0 H was less than that at 3.0 H, indicating a windward shelter effect.

At ViS1, a deviation of soil moisture content between 3.0 and 11.0 H, following periods of recharge, indicated a potential soil-moisture conservation effect in the sheltered zone. This did not occur at WoS3, due mainly to a very low soil moisture content that had little scope for variation. At WoS1, the significant trend ($p < 0.05$) of a lowering of soil moisture content with increasing distance from the southern windbreak was due to a slight physical depression in the southern section of the site.

At WoS3, strong and sustained wind speeds caused leeward soil temperature increases of up to 4°C at 3.0 H, compared to 11.0 H. Brief strong winds had little effect on the soil temperature differences. During wetter conditions, increased temperatures from a shelter effect may increase crop yields compared to unsheltered crops. During hot and dry conditions, increased temperatures may cause greater levels of stress compared to unsheltered crops. Strong winds at ViS1 did not occur on a sustained level, resulting in little difference in soil temperatures at 1.0 H to the windward side and 3.0 H to the leeward side of the windbreak. Another contributing factor to the similar soil temperatures at ViS1 was the potentially highly sheltered conditions at the windward location (at crop height) due to the 1.0 m high fynbos at the northern boundary of the cleared area. The anemometer at the windward location was elevated above the fynbos shelter effect, therefore remained unsheltered.

From the crop assessments and the wind speed data at both ViS1 and WoS3, the maximum shelter effect extended to approximately 4.0 H, followed by an intermediate zone of diminishing shelter that extended to approximately 9.0 H. The extent of the leeward shelter effect was indicated by the intermediate wind speeds recorded at 7.0 H for the second sampling period at WoS3. The fully exposed zone perhaps occurred from 9.0 H in a leeward direction. This was consistent with other reports, where leeward extent of the maximum shelter effect was estimated to extend from 3.0 to 6.0 H (Cleugh and Hughes, 2000; Cleugh, 1998; Sun and Dickinson, 1997; Hodges and Brandle, 1996; Bird, 1988; Ujah and Adeoye, 1984). Decreasing levels of shelter extended to 10.0 H (Pretzechel *et al.*, 1991; Dickey, 1988).

Possibly the most favourable weather conditions for a maximum shelter effect involves sufficient levels of soil moisture and nutrient levels (to maximise crop growth) with sustained windy conditions (to maximise crop variation in relation to the level of shelter).

1.3 Competition effect

For ViS1, similarly sheltered wind speeds (from northerly winds) and similar soils at 1.0 and 1.7 H to the lee suggested that significantly lower yields at 1.0 H were attributed to shading by the northern ViS1 windbreak. Compared to the leeward yields at 1.7 H, those at 1.0 H were significantly reduced ($p < 0.05$) for barley head number (by an average of 61%), transformed proportion of barley head$^{\text{mass}}$ from above-ground$^{\text{mass}}$ (56%), potato tuber$^{\text{mass}}$ (32%), total potato tuber number (32%), and small potato tuber number (33%).

For WoS3, similarly exposed wind speeds (from southerly winds) and similar soils at 2.0 and 0.8 H to the windward side the northern WoS3 windbreak (17.0 and 18.2 H from the southern windbreak respectively) suggested that significantly lower yields at 0.8 H from the northern windbreak were attributed to shading. Compared to the windward yields at

2.0 H, those at 0.8 H were significantly reduced ($p < 0.05$) for grain^{mass} (by an average of 57%), total^{mass} (28%), proportion of grain^{mass} from total^{mass} (by 28%), and sub-sampled^{mass} of 100 grains (by 24%, dropping from 2.09 to 1.57 g).

For SaS1, significantly reduced wheat above-ground^{mass} ($p < 0.05$) at 1.0 H was attributed to shading from the adjoining northern windbreak, compared to yields at 2.0 H. Due to the consistent soils at 1.0 and 2.0 H, crops yields could be directly compared with each. Compared to the above-ground^{mass} at 2.0 H, those at 1.0 H were reduced by 44%.

The absence of a significant shading effect ($p < 0.05$) for barley is vegetative production at ViS1 and WoS3 perhaps suggested that, unlike grain production, vegetative production of barley was not affected by shade. For ViS1, WoS3, and SaS1, a rapid recovery of yields beyond 1.0 H from the southern side of the respective northern windbreak indicated that the competitive effect was highly restricted. Windbreak shade may not be an important issue for rain fed cropping systems because competition for light in water-limited environments is of minor importance compared to competition for water.

For the soil moisture probes at ViS1, soil moisture content at 1.0 H was consistently higher compared to that at 3.0 and 11.0 H, perhaps indicating a shelter effect caused by the northern windbreak intercepting radiation and thereby reducing evaporation at 1.0 H, relative to distances further from the windbreak. Soil probes at WoS3 also did not indicate a depletion of soil moisture resulting from the southern WoS3 windbreak. Importantly, these trends suggested that the windbreaks at ViS1 and WoS3 did not compete with the adjoining crop for soil moisture.

The absence of a competition effect on the northern side of the windbreaks at each of these sites, and the absence of a decrease in soil moisture content and soil nutrient levels, suggested that the competitive interaction did not occur below the soil surface. This indicated that the windbreaks at ViS1, WoS3, and perhaps SaS1 had access to the water table, therefore used spatially distinct sources of water to the adjacent crops. If this was the case then *P. radiata*, *C. cunninghamiana*, and to a lesser extent *E. cladocalyx* may be suitable species to maximise complementarity between the windbreaks and the adjacent crops, for sites with an accessible water table.

However, below-ground competition was indicated on the northern side of the WoS1 windbreak. As conditions became drier, average soil moisture levels at 1.0 and 3.0 H diverged from a negligible level on 6 November 1998 to a 22% difference on 2 December 1998 (ie. soil moisture became 22% higher at 3.0 H, compared to 1.0 H). Although not significant ($p > 0.05$), this divergence of soil moisture at 1.0 and 3.0 H suggested a possible intensification of soil moisture uptake by the adjoining southern windbreak. The soil moisture content at 2.0 H was intermediate to those at 1.0 and 3.0 H. Therefore, the soil moisture depletion extended to 2.0 H, although in a reduced capacity compared to 1.0 H. The average above-ground^{mass} was 14% higher at 3.0 H compared to 1.0 H, further indicating an increased potential for below-ground competition for crops growing in drier conditions.

The crops growing earlier in the growing season at ViS1 and WoS3 perhaps had sufficient soil moisture to avoid competition with the adjoining windbreaks. Where there is an inaccessible water table, increased levels of competition for water might occur at the zone where trees must, like adjacent crops, rely on water from the top of the soil profile. Subsequently, recommendations of windbreak species for sites with an accessible water table may not apply for sites with an inaccessible water table. Other investigations indicated a similarly restricted extent of competition at 1.5 to 2.0 H from the adjoining windbreak (Kowalchuk and De Jong, 1995; Puri *et al.*, 1992; Baldwin, 1988; Lyles *et al.*, 1984).

Barley yield differences between 1.0 and 13.7 H were not significantly different ($p > 0.05$), indicating that the effect of unsheltered wind speeds was similar to the effect from shading. Crop yields at 1.0 and 13.7 H could be directly compared, as the soils at these locations were similar. Potato yield differences between 1.0 and 13.7 H were also not significantly different ($p > 0.05$). An exception to this was for the large potato tuber number, which was significantly higher ($p < 0.05$) at 13.7 H, compared to 1.0 H. This suggested that large tuber production was reduced more by the effect from competition than by the effect of unsheltered wind speeds.

2 RECOMMENDATIONS

In agreement with extension officers and farmers in the Wolseley region, windbreaks should be established as double rowed windbreaks, with trees spaced 1.5 m apart from each other and arranged in a staggered pattern. For rapid development of an effective shelter effect, windbreak networks could be spaced quite closely (50 to 100 m) from each other. As the windbreaks increase in height, and subsequently the extent of shelter from each windbreak increases, then alternate windbreaks could be removed. This should be done only when the removal of alternate windbreaks does not affect the consistency of the shelter effect. This process of removing alternate windbreaks could continue in a similar pattern to a forestry thinning regime. Therefore, if the mature tree height of a windbreak were 25 m, then the final distance between the remaining windbreaks would be 150 to 200 m.

Many windbreaks remain unpruned to enhance their shelter effect, which is at the expense of timber quality (Rukuni, 1998; Smail, 1971). However, optimum porositymust be ensured. In an effort to produce more clearwood while maintaining the shelter benefit, windbreaks should be double-rowed and double-storied. This can be achieved either by pruning every alternate tree or by pruning one of the rows entirely while the other row remains unpruned to maintain shelter from low draught winds (Rukuni, 1998; Smail, 1971).

A double-rowed *P. radiata* windbreak in New Zealand had every second tree pruned to a height of 6.5 m. The pruned trees produced a much greater proportion of high value pruned logs (12%) compared to the non-pruned trees (2%) from the total tree harvest. The non-pruned trees produced a greater proportion of pulp logs (36%) compared to the pruned trees (14%) from the total tree harvest (Rukuni, 1998).

Windbreaks could also be thinned, provided that an effective level of porosity was maintained throughout each windbreak. In the case of a 10-year old *C. cunninghamiana* windbreak, an entire row of a double rowed windbreak could be removed without severely reducing the level of porosity. Windbreak thinning would provide valuable intermediate sources of revenue for the farmer, as in the case of other agroforestry systems. Earlier thinnings would be useful for low value products such as firewood, pulpwood, and fence posts. Accompanied by appropriate pruning, later thinnings would provide the potential for higher quality wood products, such as veneer wood.

Therefore, effective windbreak networks in the Western Cape Region would be required to be orientated in an east-west direction (or more specifically from a south-west to north-east direction) to counter south-easterly winds and / or north-westerly winds. From the evidence of the extent of shelter at ViS1 and WoS3, perhaps a series of windbreaks spaced at 9.0 to 10.0 H would provide a consistent shelter effect with the assumption that the shelter effect also extended to 1.0 or 2.0 H on the windward side. Bird (1998) noted that for practical purposes it may be necessary to site windbreaks at around 10.0 to 15.0 H apart to obtain the most economic response in terms of pasture and animal production.

Perhaps strips of shade tolerant crops could be planted up to 2.0 H to the lee of the shaded (southern) side of windbreaks to reduce the negative shading effect. However, access tracks adjoining each windbreak side would probably be a more effective use of the potential competition zone.

Despite the benefits of very tall trees, Peltola (1996) noted that increased tree heights resulted in increased risk of windthrow (turning moments arising from the dynamic load of the wind). Using computer simulations on *Pinus sylvestris*, trees with a height exceeding 24 m were at much greater risk of being uprooted than trees 20 m in height but with the same taper. The shortest trees (16 m in height) were the least likely to be uprooted, although these results would vary with stand density and above and below-ground morphology. The optimum profile of tree crowns is upright rather than rounded. From personal observations, large trees consistently appeared to have poor profiles and hence poor porosity levels, and also exerted high levels of competition due to their large size. Therefore, harvesting of trees exceeding 16 m is recommended, provided that adequate shelter to the crops were quickly recovered by newly planted windbreaks.

Where ground water is not accessible to windbreak trees, it is vital to employ management strategies to reduce water use by trees, otherwise crop productivity is unlikely to profit fully from the benefits offered by shelter. Planners should select tree species that have a low stomatal conductance, thereby a low demand for water. Species should also have root systems that do not spread laterally for large distances near the soil surface. Where the trees have access to the watertable, species should be selected that have rooting habits that enable ground water access, but at the same time do not use so much water that ground water levels decline in the long term. As strategies for limiting transpiration are not as crucial in these locations, a greater scope of trees species would be available thereby increasing the range of potential tree products (Smith *et al.*, 1998).

A further strategy for the reduction of ground water demanded by windbreaks is pruning of the canopies. Planners must decide on the appropriate timing and severity of pruning, and also the desired shape and porosity of the windbreak so as to minimise the demand for water by the trees while maximising the shelter benefits (Smith *et al.*, 1998). Shading may also be diminished by choice of windbreak species, orientation, and appropriate tree thinning and branch pruning schedules (Nuberg, 1998).

Frequent root pruning of windbreaks reduced competition between the tree and crop components (Huxley *et al.*, 1994; Korwar and Radder; 1994, Singh *et al.*, 1989; and Myburgh and Viljoen, 1979). In tropical India, Korwar and Radder (1994) demonstrated how root pruning of *Leucaena* hedgerows increased sorghum grain yields by 33%. However, root pruning may have to be a frequent procedure due to rapid root re-growth. Myburgh and Viljoen (1979) suggested that when extensive windbreak establishment was undertaken in an area, root pruning could be done economically if done on a co-operative basis. Provided root pruning does not unduly interfere with the growth and stability of windbreak trees, this practice could possibly become standard management of windbreaks.

If this is the case, then it will be necessary to include the yield gain from root pruning as well as the cost of the practice in calculating the economic return of windbreak systems (Nuberg, 1998).

The choice of tree species was the most important factor to be considered for windbreak technology (Puri and Bangarwa, 1992). The critical requirement was that the species be adapted to the climate and soil type. In most localities, locally adapted species should be considered first, followed by species imported from other regions.

Windbreak species should be selected on the basis of high survival and growth rates, crown form, compatibility with adjacent crops, cold and drought hardiness and pest resistance. Trees should have a potential height of 5 to 30 m and crown spread should not exceed 3 m to minimise competitive interactions. Windbreaks planted for soil protection should include species that are long lived and that will attain a substantial mature height. The most effective windbreak species provide a semi-permeable barrier to wind over their full height, from the ground to the crowns of the tallest trees (Khan and Ehrenreich, 1994; Cunningham, 1988).

Casuarina species have the greatest potential as effective windbreaks due to many favourable characteristics, such as a high tolerance to harsh environmental conditions, a bushy and thick crown that has a suitable level of porosity, delayed shedding of lower branches, wind firmness of roots, rapid growth for early crop protection, longevity, pest and disease resistance, and a good coppicing ability following harvesting. In New Zealand, *P. radiata* windbreaks effectively provide shelter for livestock from cold winds. Regular trimming of these windbreaks on their sides and tops prevent too much shading of pastures (Boland, 1997).

Initial preference for *P. radiata* windbreaks on orchard farms in the Western Cape of South Africa was shifting towards *C. cunninghamiana* windbreaks (Eicker *et al.*, 1986; Pienaar, 1987). From personal observations, the most suitable tree species in the Western

Cape is *C. cunninghamiana*. Although its timber uses are restricted as it is difficult to saw and season, the wood splits easily and makes an excellent fuel (Doran, 1997).

In comparison, eucalypts as windbreaks have only a limited life because of the shedding of the lower branches. This is evidenced by the extensive use of *E. cladocalyx* in Australia and *E. diversicolor* in South Africa, for eucalypt windbreaks (Boland, 1997). From personal observations, provenance trials in the Western Cape Region indicated that *E. gomphocephela* and perhaps *E. botryoides* delayed the shedding of lower branches thereby potentially increased their effective life as windbreaks (compared to other Eucalypt species). However, even *E. gomphocephela* and *E. botryoides* compared poorly to *C. cunninghamiana* as a windbreak species.

The possibility of introducing indigenous trees for windbreak systems in the Western Cape should be encouraged. However, caution must be made of the suitability of 'local' species. It would be foolish to automatically assume that certain South African tree species must be more suitable (perhaps emotionally or politically) for selection in the Western Cape than any exotic species. *C. cunninghamiana* may be better adapted, and therefore better serving to the farming community, to conditions in the Western Cape than any potential windbreak species that is indigenous to South Africa.

Windbreak research in the Western Cape is in a preliminary stage. Research on a larger scale is recommended, involving the planting of extensive windbreak systems. Different tree species, different crop species, and different windbreak designs at different intensities are required to fully investigate the potential of windbreaks on farms. Preferably, the research should be located in various locations in the Western Cape to investigate the effects of site variability.

The benefits of windbreaks in townships throughout South Africa should not be overlooked. The level of wind speed reductions recorded in the sheltered zones at ViS1 and WoS3 would have a significant protective effect for houses, many of which are vulnerable to damage from high wind speeds.

3 REFERENCES

Baldwin CS. (1988) The influence of field windbreaks on vegetable and speciality crops. Agric. Ecosyst. Environ. 22 / 23: 191 - 204

Bird PR. (1998) Tree windbreaks and shelter benefits to pasture in temperate grazing systems. Agrofor. Syst. 41: 35 - 54.

Bird PR. (1988) Financial gains of trees on farms through shelter. Proc. Internat. Forestry Conf. For the Australian Bicentary 1988. Aust. Forest Development Institute, Vol 2. In: Bird PR. (1998) Tree windbreaks and shelter benefits to pasture in temperate grazing systems. Agrofor. Syst. 41: 35 - 54.

Boland, DJ. (1997) Selection of species and provenances for planting. In: Doran JC. and Turnbull JW, (eds) (1997) Australian trees and shrubs: species for land rehabilitation and farm planting in the tropics. ACIAR Monograph. Canberra, Australia, 384 pp.

Cleugh HA. (1998) Effects of windbreaks on airflow, microclimates and crop yields. Agrofor. Syst. 41: 55 - 84.

Cleugh HA., Miller JM. and Bohm M. (1998) Direct Mechanical effects of wind on crops. Agrofor. Syst. 41: 83 - 112.

Cunningham RA. (1988) Genetic improvement of trees and shrubs used in windbreaks. Agric. Ecosyst. Environ. 22 / 23: 483 - 498.

Dickey GL. (1988) Crop water use and water conservation benefits from windbreaks. Agric. Ecosyst. Environ. 22 / 23: 381 - 392.

Doran JC., Turnbull JW., Martensz PN., Thomson LAJ., and Hall N. (1997) Introduction to the species digests In: Doran JC. and Turnbull JW, (eds) (1997) Australian trees and shrubs: species for land rehabilitation and farm planting in the tropics. ACIAR Monograph. Canberra, Australia, 384 pp.

Eicker R., Viljoen GK. and Myburgh J. (1986). Efficiency of pine windbreaks for protecting apple orchards. Deciduous Fruit Grower, January, pp. 15 - 20.

Hodges L. and Brandle JR. (1996) Windbreaks: an important component in a plasticulture system. Hort. Technology 6: 177 - 181.

Huxley PA., Pinney A., Akunda E. and Maraya P. (1994) A tree / crop interface orientation experiment with a *Grevillia robusta* hedgerow and maize. Agrofor. Syst. 26: 22 - 45.

Khan GS. and Ehrenreich JH. (1994) Effect of increasing distance from *Acacia nilotica* trees on wheat yield. Agrofor. Syst. 25: 23 - 29.

Korwar GR. and Radder GD. (1994) Influence of root pruning and cutting interval of *Leucaena* hedgerows on performance of alley cropped *rabi* sorghum. Agrofor. Syst. 25: 95 - 109.

Kowalchuk TE. and De Jong E. (1995) Shelterbelts and their effect on crop yield. Can. J. Soil Sci. 75: 543 - 550.

Lyles L., Tatarko J. and Dickerson JD. (1984) Windbreak effects on soil water and wheat yield. Trans ASAE 20: 69 - 72. In: Sun D. and Dickenson GR. (1994) A case study of shelterbelt effect on potato (*Solanum tuberosum*) yield on the Atherton Tablelands in tropical north Australia. Agrofor. Syst. 25: 141 - 151.

Myburgh J. and Viljoen GK. (1979) Protection of deciduous fruit trees against wind. The Deciduous Fruit Grower, March. pp. 72 - 78.

Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Peltola H. (1996) Model computations on wind flow and turning moment by wind for Scots pines along the margins of clear - cut areas. For. Eco. Man. 83: 203 - 215.

Pienaar P. (1987) Wind protection in orchards: effect on growth, production and fruit quality. Deciduous Fruit Grower, August. pp. 291 - 295.

Pretzechel M., Bohme G. and Krause H. (1991) Effects of shelterbelts on crop yield. Feldwirtschaft 32(5): 229 - 231. In: Nuberg IK. (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. Agrofor. Syst. 41: 3 - 34.

Puri S. and Bangarwa KS. (1992) Effects of tree yield of irrigated wheat crops in semi - arid regions. Agrofor. Syst. 20: 229 - 241.

Rukuni D. (1998) Timber production from shelterbelts. Newsletter of the research Development Division, Zimbabwe Forestry Division. 10 (2).

Singh RP., Ong CK. and Saharan N. (1989) Above and below - ground interactions in alley - cropping in semi - arid India. Agrofor. Syst. 9: 259 - 274.

Smail P. (1971) The need for shelter. Farm Forestry 19 (20): 48 - 50.

Smith DM. Jarvis PG. And Odongo JCW (1998) Management of windbreaks in the Sahal: the stategic implications of tree water use. Agrofor. Syst. 40: 83 – 96.

Sun D. and Dickinson GR. (1997) Early growth of six native Australian tree species in windbreaks and their effect on potato growth in tropical northern Australia. For. Eco. Man. 95: 21 - 34.

Ujah JE. and Adeoye KB. (1984) Effects of shelterbelts in the Sudan savanna zone of Nigeria on microclimate and yield of millet. Agric. For. Meteorol. 33: 99 - 107. In: Ritchie KA. (1988) Shelterbelt plantings in semi-arid areas. Agric. Ecosyst. Environ. 22 / 23: 425 - 440.