TREE WINDBREAK FUNCTION, ROOT DISTRIBUTION AND BIOMASS PRODUCTION IN FLORIDA

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2009

ACKNOWLEDGMENTS

I would like to thank my supervisory committee chair, Dr. Donald L. Rockwood, and cochair, Dr. Michael G. Andreu, for their academic guidance and support throughout my time here at the university. Special thanks go to the members of my committee, Drs. Shibu Jose, Christina L. Staudhammer, Craig K. Chandler, and William S. Castle, for their guidance and critical evaluation of my work from the very beginning. I appreciate Dr. Staudhammer's continuous guidance during data analysis.

I am grateful to all individuals and institutions that supported this research directly and indirectly. Weather stations were purchased by the University of Florida (UF)-Gulf Coast Research and Education Center (GCREC)-Plant City Campus Technology Fund. The College of Agricultural and Life Sciences (CALS/IFAS) also provided matching funds for my doctorate program. A graduate student grant from the Sustainable Agriculture Research and Education (Southern Region) Program (GS08-075) supported the field work.

I am indebted to Chuck and Rosa Obern and their staff at C&B Farms. They were always available when I needed help, and their place was always open for me. I would like to thank them for their continued support, accommodations, and farm equipment they provided throughout the study. I would also like to thank Southwest Florida Research and Education Center (SWFREC) at Immokalee for allowing me to conduct research there. Special thanks go to Dr. Robert E. Rouse and James M. Knowles, who maintained the weather stations.

My family always supported me and my work. I thank my wife, Binita and son, Abidan who sacrificed for me to pursue this degree. My parents and in-laws have always been a source of inspiration to me. I express my deep gratitude to all of them.

I could not have done this work without the help from the phytoremediation lab team. Special thanks to Paul Proctor, Brian Becker, Bill McKinstry, Prakash Subedi, and Kathy Slifer who spent countless hot and sweaty days in the field with me.

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LIST OF ABBREVIATIONS

AWS	Automated weather station
C	Carbon
CALS	College of Agricultural and Life Sciences
COMET-VR	Voluntary Reporting of Greenhouse Gases-CarbOn Management Evaluation Tool
DBH	Diameter at 1.3 m (breast height)
FAWN	Florida Automated Weather Network
FDACS	Florida Department of Agriculture and Consumer Services
GCREC	Gulf Coast Research and Education Center
IFAS	Institute of Food and Agricultural Sciences
IPCC	Intergovernmental Panel on Climate Change
NRCS	Natural Resources Conservation Service
RBS	Randomized branch sampling
RH	Relative humidity
SARE	Sustainable Agriculture Research and Education
SCSA	Stem cross sectional area
SWFREC	Southwest Florida Research and Education Center
UF	University of Florida
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USDA	United States Department of Agriculture

Abstract of Dissertation Presented to the Graduate School
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Requirements for the Degree of Doctor of Philosophy

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December 2009

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Cochair: Michael G. Andreu
Major: Forest Resources and Conservation

Windbreaks increase crop yield and quality simply by reducing wind and modifying microclimate. They also can control pathogen spread, mitigate livestock odor, and sequester atmospheric carbon. However, competition at the windbreak-crop interface reduces crop yield. This south Florida study was conducted to examine single-row eastern redcedar (*Juniperus virginiana*) and cadaghi (*Corymbia torelliana*) windbreak functions and their effects on temperature and relative humidity (RH) on the leeside of the windbreak. Root distribution and biomass production of cadaghi windbreak trees were also studied. Wind speed, temperature and RH at 2 m above the ground were measured using automated weather stations (AWS) at different distances from the windbreaks. Roots in soil trench faces at 2 m and 4 m from the windbreaks were used to study root distribution and test L_V=2N (where L_V is the root length density (root length per unit volume of soil) and N, the number of roots) relationship in cadaghi. Cadaghi trees were destructively sampled to develop biomass equations and estimate oven-dry weights in various aged cadaghi windbreaks.

Windbreaks reduced wind, but wind reduction varied with open wind speed and wind direction. Wind reduction on the leeside of redcedar windbreak was at least 64% at two times the windbreak height (2H) and 22% at 14H. When wind direction was nearly perpendicular to the windbreak, wind speed at 2H on the leeside of redcedar windbreak was ~5% of the open wind speed, and the relatively porous cadaghi windbreak was ~3-30% and <50% at 4H and 6H, respectively. Wind speed at 2H on the leeside of redcedar windbreak was always lower than 18% of the open wind speed when wind direction was between 45 and 135 degrees to the windbreak, which was equivalent to windbreak porosity. Cadaghi windbreaks also had similar wind reduction. Wind reduction was observed up to 31H, but wind speed on the leeside of the windbreak was generally lower than in the open throughout the study. Cadaghi windbreaks reduced wind even during a tropical storm. On the leeside of the windbreaks, daytime temperatures closer to the windbreaks were up to 3% higher than in the open. However, temperatures at locations closer to the windbreaks were up to 1.9° C lower than in the open during cold fronts.

Cadaghi roots were restricted to the upper 50 cm of the soil. Root number was highly variable and significantly higher in older windbreaks. Root distribution had no distinct pattern. Cadaghi roots were anisotropic, and most roots showed horizontal growth preference. Both N_X (number of roots exiting the frontal face of the trench wall (X)) and N_{AVG} (average root number measured in three-dimensions: N_X, N_Y and N_Z, where Y is the vertical face perpendicular to X and Z the basal horizontal face) were significant variables for estimating L_V. The N coefficient was not significantly different from 2 when N_{AVG} was used. Distribution of L_V and root weight with depth were similar to that of N.

Diameter at breast height (DBH) alone was sufficient to predict cadaghi crown and whole tree weight, but height was a necessary variable for trunk weight estimation. Average oven-dry whole tree weight ranged between 31 and 708 kg for 2- and 20-year-old windbreaks. Oven-dry whole tree weight/100 m of windbreak ranged between 802 and 20,145 kg in the same windbreaks.

Tree windbreaks effectively modify microclimate and enhance Florida farm crop yield and quality. Because fast-growing cadaghi efficiently sequester more carbon than other species used for windbreaks, landowners can expect higher carbon credit payments, where available. This can offset the cost of land occupied by windbreaks in short period.

CHAPTER 1
GENERAL INTRODUCTION

Windbreaks are used worldwide to mitigate wind-related agriculture problems. In the US Great Plains, windbreaks were planted from 1935 through 1942 in response to a decade long decrease in agricultural income, a series of dust storms and economic collapse in the wheat and corn belts. The primary objective was to stabilize microenvironment in the area. A National Windbreak Program in Australia was started in 1993 to study the impact of windbreaks on microclimate and crop production (Cleugh et al., 2002). Both projects were successful and showed promising results (Munns and Stoecker, 1946; Cleugh et al., 2002). Windbreaks have also been used in South America (Peri and Bloomberg, 2002) and many developing countries (Nair, 1993).

Apart from primarily reducing wind, windbreaks modifed microclimate (Cleugh, 1998, 2002; Peri and Bloomberg, 2002; Sudmeyer and Scott, 2002a; Brandle et al., 2004), reduced soil erosion and conserved nutrients (Sudmeyer and Scott, 2002a; Brandle et al., 2004; Kulshreshtha and Kort, 2009), and enhanced crop growth and increased crop yield (Cleugh, 1998; Nuberg et al., 2002; Sudmeyer and Scott, 2002b; Brandle et al., 2004). Windbreaks also provided many ecosystem services and environmental benefits including carbon sequestration and biodiversity conservation (Cleugh et al., 2002; Maize et al., 2008; Kulshreshtha and Kort, 2009). They also helped manage the spread of pathogens such as citrus canker (*Xanthomonas campestris* pv. *citri*) in South America and Australia (Leite and Mohan, 1990; Gottwald and Timmer, 1995; Muraro et al., 2001).

Florida is one of the leading agricultural states in the nation. About 47,500 commercial farms produced a variety of crops, primarily vegetables and citrus, on approximately 3,743,348 ha in 2008. Florida was second in vegetable production and first in citrus production in the nation in 2007. Sales of vegetables alone exceeded $1.5 billion in 2008. The overall economic impact of Florida agriculture was estimated to be about $100 billion annually (FDACS, 2008).

However, Florida agriculture still faces major challenges such as freezes, tropical storms and/or hurricanes, high winds, infertile soil, and diseases. Because of its geographical location, tropical storms and hurricanes from both the Gulf of Mexico and the Atlantic Ocean strike Florida frequently. Soil moisture is usually low because of the sandy soil and dry seasons. Also, Florida soils have relatively low levels of organic matter and cation exchange capacity (McAvoy, 2007), and nutrients easily leach during intense rain. Farms are also subjected to regular high winds. As wind eroded soils in Australia had large amounts of soil nutrients (Nuberg, 1998; Sudmeyer and Scott, 2002a), farms subjected to high winds are susceptible to soil erosion and nutrient loss. Florida’s citrus industry is severely impacted by citrus canker and greening (caused by *Candidatus* Liberibacter asiaticus).

Wind scarring is another factor that reduces the quality of Florida agricultural products for fresh market. Wind scar occurs from sand abrasion and rubbing of plant parts primarily on young tender fruits. Therefore, windbreaks of ryegrass (*Lolium perenne*) (Workman et al., 2003) and sugarcane (*Saccharum* spp.) are used in vegetable farms to protect crops from wind damage. Wind speeds as low as 6.7 m s^{-1} have been reported to cause wind scarring in citrus (Metcalf, 1937). Wind scar accounted for 33.8 and 27.1% of the total defects in the Indian River grapefruit in 1990/91 and 1991/92 seasons, respectively. Wind scarring coincided with the period of high winds. Young citrus fruits were susceptible to wind damage in spring when high speed winds were frequent (Miller and Burns, 1992). Fruits in the outside rows suffered severe wind scar (Albrigo, 1976). In the middle rows, fruits from tree tops had significantly greater wind scar than the fruits in the lower canopy (Albrigo, 1976; Stover et al., 2004). Removal of low hanging branches also increased wind scar in lower canopy in Orlando tangelo (Morales and Davies, 2000). Wind also damaged the delicate skin of carambola (*Averrhoa carambola*) fruit in Florida (Miller et al., 1990; Núñez-Elisea and Crane, 1998; Núñez-Elisea and Crane, 2000). Damage was severe in the outer canopy with more than 58% of the fruit harvested showing wind damage (Núñez-Elisea and Crane, 2000).

After extensive canker spread by 2004/05 hurricanes, windbreaks were promoted to manage canker in Florida (http://fcircc.org/extension/windbreaks/index.htm) and some citrus growers are planting windbreaks to protect citrus crop from canker and wind damages. Because of the urgency for windbreaks, fast-growing trees such as cadaghi (*Corymbia torelliana*), eucalypts (*Eucalyptus grandis* and *E. amplifolia*) and Australian pine (*Casuarina* spp.) are highly preferred due to their fast growth and evergreen nature. Cadaghi and eucalypts are not regulated in Florida, and are widely used in windbreaks (Rockwood et al., 2008). Though Australian pine is regulated because of its invasiveness, an amendment of the Florida Statutes in 2009 allows commercial citrus growers only in Indian River, St. Lucie, and Martin Counties, where canker is widespread, to use Australian pine for windbreaks with a special permit. Among three species of Australian pine (*C. glauca, C. equisetifolia and C. cunninghamiana*) in Florida, *C. cunninghamiana* is considered the best for windbreaks because of its performance in other citrus growing countries and its least invasive potential (Castle et al., 2008).

Trees are usually planted in multiple rows in windbreaks for optimum results, but windbreaks of only fast-growing species are rarely used. Because of limited space, current tree windbreaks in Florida are mostly of single rows. In areas where fast-growing species were used, trees were usually combined with other species (Sun and Dickenson, 1997). There are limited studies on the performance of fast-growing species windbreaks, planted either alone or in combination with other species (see Sun and Dickinson, 1997; Peri and Bloomberg, 2002). There is also little or no information available on the widely planted cadaghi.

One of the major issues in windbreak planting is windbreak-crop competition. Competition for resources significantly impacted crop growth and reduced yield near windbreaks (Sudmeyer et al., 2002a, 2002b; Woodall and Ward, 2002; Unkovich et al., 2003). Therefore, above- and belowground competition must be minimized for optimal crop production. Underground competition near the windbreaks can be intense because fast-growing species produced relatively higher root length density (root length per unit volume of soil, L_V) compared to slow-growing species (Coleman, 2007). Also, non-native species were generally competitive (Callaway and Aschehoug, 2000; Lopez-Zamora et al., 2004; Collins et al., 2007; Tamang et al., 2008). To manage underground competition effectively, information such as root architecture, distribution (both horizontal and vertical) and branching pattern is important.

Carbon sequestration is an indirect benefit of windbreaks. When trees and shrubs are planted, carbon sequestration potential of farms significantly increases compared to monoculture crops. Incorporating multiple species in windbreaks increases nutrient use. Therefore, mixed species windbreaks can sequester carbon more efficiently. Along with the storage in aboveground parts, more than half of the carbon sequestered by trees is stored in the soil (Montagnini and Nair, 2004). Forests have received attention lately for their capacity to reduce carbon emissions, and extensive work has been done to estimate biomass in forests (Lambert et al., 2005; Cole and Ewel, 2006; Vallet et al., 2006; Alamgir and Al-Amin, 2008; Nogueira et al., 2008), but biomass production potential of windbreaks is little known and often neglected. For accurate biomass estimation of windbreaks, separate equations need to be developed for windbreak grown trees.

In summary, windbreaks of different species and configurations have demonstrated potential for mitigating various wind-related agricultural problems across the globe (Gottwald and Timmer, 1995; Cleugh et al., 2002, Peri and Bloomberg, 2002; Brandle et al., 2004). Since wind-related agricultural issues in Florida are similar to those in other parts of the globe, windbreaks could potentially be used to mitigate such problems. However, single-row windbreaks and windbreaks of fast-growing trees such as that of cadaghi must be evaluated to see if they produce the same results and benefits of other multiple-row windbreak species. Root distribution of windbreak trees also need to be studied to effectively manage underground competition.

The objectives of this study were to determine (a) single-row tree windbreak function and its effect on microclimate, (b) root distribution of windbreak grown cadaghi trees, and (c) biomass in various aged cadaghi windbreaks. The hypotheses of this research were:

Hypothesis 1: Single-row windbreaks of eastern redcedar and cadaghi reduce wind and modify microclimate.

Hypothesis 2: Older cadaghi trees produce comparatively more roots and number of roots (N) is a good predictor of root length density (root length per unit volume of soil, L_V).

CHAPTER 2
LITERATURE REVIEW

Eastern Redcedar and Cadaghi Species

Fast-growing evergreen species are ideal for windbreaks as they grow rapidly and provide year-round protection. Using evergreen species require fewer rows as they retain foliage throughout the year and maintain relatively uniform porosity. Therefore, windbreaks of evergreen species occupy less land.

Cadaghi, also known as *Eucalyptus torelliana* in earlier literature and now *Corymbia torelliana*, is an ideal windbreak species (Sun and Dickinson, 1997). It is an evergreen tropical rainforest species native to Australia. With broad and hairy leaves, its canopy intercepted more light than *E. camaldulensis* and *E. grandis* (Schumacher and Poggiani, 1993) and is probably the densest of all the eucalypts (FAO, 1979). It is susceptible to frost damage and is suitable for areas where temperature remains above -3° C. Creamy white flowers bloom in clusters in October in its native range and capsules ripen in January and February. Each capsule produced about 16 seeds (Wallace et al., 2008).

In its natural range, most seeds (88%) were dispersed by gravity, but the 12% retained in the capsules were embedded in resin and were dispersed in a non-standard method by four species of stingless bees: *Trigona carbonaria*, *T. clypearis*, *T. sapiens*, and *T. hockingsi* (Wallace et al., 2008). Outside its natural range, seed dispersal was carried out only by *T. carbonaria* (Wallace and Trueman, 1995). Seed dispersal by bees was the longest known distance for any insect-meditated seed dispersal (Wallace and Trueman, 1995; Cain et al., 2000; Wallace et al., 2008). Seeds were in bee hives as far as 220 m (Wallace et al., 2008), and more than 300 m (Wallace and Trueman, 1995) from the parent tree. Clonal propagation of cadaghi has been studied in other parts of the globe (Gupta et al., 1983; Bisht et al., 2002; Trueman and Richardson, 2007). However, it is currently propagated from seeds in Florida.

Fast-growing cadaghi can grow up to 25 m tall. It grew up to 4.6 m tall, with 6.9 cm DBH in 2.5 years when planted in a three-row windbreak with *E. microcorys*, *Callistemon salignus, C. uiminallis, Melaleuca armillaris* and *M. linariifolia* (Sun and Dickinson, 1997), and 50 cm tall in 10 weeks when intercropped with cabbage (Nissen et al., 1999). In addition to fast growth, retention of lower branches qualifies it as a good windbreak species. It has been widely used in windbreaks in Australia and South America. Though closely related to eucalypts, the species did not have toxic allelopathic chemicals and its leaf mulch did not affect cabbage growth (Nissen et al., 1999). It also had some medicinal value of antibacterial and gastroprotective nature (Adeniyi et al., 2006). The species was also suitable for pulpwood (Guha et al., 1970).

Eastern redcedar (*Juniperus virginiana*) is one of the major windbreak species in the US Great Plains and is native to the forests of the eastern and central US. It is an evergreen species that can grow 10-20 m tall. The crown is dense and is usually columnar or pyramidal. It is the most widely distributed conifer in the eastern US. Arkansas, Tennessee, Kentucky and Missouri have the highest acreage of redcedar and account for about 53% of the nation’s redcedar.

Small inconspicuous flowers bloom at the ends of twigs from March to May, and cones are ready for harvest in fall (September-November). Only 10-years or older trees bear fruit. Seed dispersal is predominantly by birds, but some mammals also dispersed the seed (Horncastle et al., 2004). Its berries are food for many birds and mammals, and its foliage is eaten by many browsers. Its dense crown also provides shelter to many species of birds. Though a large number of seeds is produced every year, the species is generally propagated by cuttings (USDA NRCS, 2009).

It is drought, heat, and cold tolerant and grows best on deep, moist, and well-drained sites. It is the major colonizer of abandoned pastures and cleared and degraded lands in the southeastern US. The species is fire intolerant and spread rapidly in absence of fire (Bragg and Hulbert, 1976). It was historically controlled using fire, and fire exclusion increased its encroachment into the US Great Plain grasslands (Hoch et al., 2002).

Every part of redcedar is marketable, and the industry totaled about $60 million per year (Gold et al., 2005). It is one of the top five Christmas trees and is commercially sold as sawtimber. Resistant to rot, it is widely used as fence posts. Redcedar seedlings are used as stock for grafting ornamental juniper clones. Its wood has moth-repelling properties, is used in wardrobes and closet linings, and is also used for furniture, flooring, scientific instruments and household items. Many tribes used the species as incense for purification and ritual (Kindscher, 1992).

Eastern redcedar leaves contain Podophyllotoxin, a medicinal compound which is commercially extracted from roots and rhizomes of the Indian mayapple (*Podophyllum emodi*) (Kupchan et al., 1965; Cushman et al., 2003). The compound is used to manufacture drugs for treatment of cancer, rheumatoid arthritis, genital warts, psoriasis and multiple sclerosis (Stahelin and von Wartburg, 1991; Giri and Narasu, 2000; Lerndal and Svensson, 2000).

Windbreak Performance

Windbreaks are one of the widely used agroforestry systems. Functional windbreaks reduced wind erosion, improved microclimate, reduced wind damage, and increased crop and livestock production (Garrett and Buck, 1997). Windbreaks have also been used to manage the spread of pathogens in agricultural crops such as citrus (Leite and Mohan, 1990; Gottwald and Timmer, 1995) and for livestock odor mitigation (Tyndall and Colletti, 2007).

Windbreak effectiveness largely depends on the characteristics of the planted species such as height, branching pattern, crown length and width, foliage retention and planting design. Evergreen species with dense and long crowns extending from the base and uniform porosity are generally preferred for windbreaks. Porosity in the bottom half of the windbreak was a good predictor of minimum relative wind speed and was useful in evaluating windbreaks (Loeffler, 1992). However, livestock browsing significantly increased basal porosity (Sudmeyer and Scott, 2002a). A change in porosity with height also occurs in some self-pruning species such as *E. grandis*. This creates large gaps leading to jetting, which combined with increased turbulence, less vegetation cover and drier soil, increased soil erosion next to windbreaks (Sudmeyer and Scott, 2002a).

Windbreak height determines the distance of wind reduction on the leeside. Though ten times the windbreak height (10H) is the internationally accepted protected distance, wind reduction has been reported up to 30H (Cleugh, 2002a; Cleugh et al., 2002) and 36H (Sudmeyer and Scott, 2002a) in Australia. Pine (*Pinus* spp.) windbreak (15% porosity) reduced wind up to 80% at 25H (Cleugh, 2002b) with minimum wind speed at 6H (Cleugh 2002a; Vigiak et al., 2003). However, in Denmark, coppice willow (*Salix* spp.) windbreak reduced wind up to 86% at 7H (Foereid et al., 2002).

Windbreak porosity determines the degree of wind reduction. Wind reduction on the leeside was equivalent to 1-β, where β is the windbreak porosity (Cleugh et al., 2002, Cleugh and Hughes, 2002). For example, windbreaks of 30% porosity reduce wind speed by 70% on the leeside. In Argentina, a windbreak of less than 15% porosity reduced wind speed by 85% at 1H, semi-permeable (porosity from 15-45%) windbreak by 75% at 4H, and permeable (porosity more than 45%) windbreak reduced wind speed by 45% at 2H (Peri and Bloomberg, 2002). A single-row poplar windbreak with 0.3 m inter-tree distance and less than 15% porosity also reduced wind speed up to 85% at a distance of 1H on leeside (Peri et al., 1998). Dense windbreaks produced smaller sheltered zones (Wang et al., 2001), but permeable windbreaks provided maximum protection between 4H and 12H in Australia (Nuberg, 1998). In Argentina, maximum protection was observed at 18H for permeable, 15H for semi-permeable and 10H for dense windbreaks, where wind speed was 70% of the open wind speed (Peri and Bloomberg, 2002).

The extent of protection also depends on the wind direction and windbreak porosity. Constant change in wind direction reduced the performance of windbreaks in Australia (Sudmeyer and Scott, 2002a). Aerodynamic porosity decreased when the wind direction shifted from perpendicular to oblique (Cleugh, 1998), and better results were obtained when the orientation of the windbreak was perpendicular to the wind. Maximum wind reduction occurred at 6H when wind direction was perpendicular to the windbreak (Cleugh, 2002b). Where wind direction changes constantly, windbreaks should be planted around the field for optimal results.

Soil erosion by wind is one of the major agricultural problems around the world. It significantly depleted soil fertility where nutrients occurred in the upper few centimeters of soil (Peri and Bloomberg, 2002). In South Australia, wind transported soil contained four times more nitrogen, five times more phosphorus and eight times more organic carbon compared to soil in the field from which it was derived (Nuberg, 1998). Wind transported soil had 1.4-6 times higher proportions of silt, clay, organic matter and nutrients than field top soil (Sudmeyer and Scott, 2002a). Similar ratios were observed in other studies (Leys and McTainsh, 1994; Larney et al., 1998). Though clay and silt particles are easily removed from the surface at lower wind speed, sand particles, however, need relatively higher wind speed. Large soil particles such as windborne sand cause physical abrasion to vegetables and fruits. Soil contamination of vegetables and fruits is another major issue.

Wind reduction and alteration of turbulence changed microclimate on the leeside (McNaughton, 1988). It usually occurred in the quiet zone between 8H and 10H (Cleugh and Hughes, 2002). Though change in microclimate created a suitable environment for crop growth, it was relatively less important compared to wind reduction (Cleugh, 2002b; Sudmeyer and Scott, 2002a,b) and was economically less important to crop growth (Cleugh, 1998; Sudmeyer and Scott, 2002a). Temperature slightly increased on the leeside during the day, but decreased near the windbreak at night (Bird et al., 2002; Foereid et al., 2002). There was an inverse relationship between wind reduction and temperature modification. Maximum temperature was recorded at the location where the wind speed was reduced the most (Cleugh et al., 2002). The distance of temperature modification was also less compared to wind reduction. For example, wind reduction extended up to 30H, but temperature and RH modification was observed only up to 12H (Cleugh et al., 2002; Cleugh and Hughes, 2002; Sudmeyer and Scott, 2002a). In Denmark, microclimate modification was observed only up to 4-7H (Foereid et al., 2002).

Windbreaks also reduced canker (*Xanthomonas campestris* pv. *citri*) spread more effectively than copper bactericide, a standard method widely used for canker control (Gottwald and Timmer, 1995). Rain splashes were the major causes of local canker dispersal (e.g., between trees in nursery), and long-distance dispersal (between groves) occurred during blowing rainstorms (Gottwald et al., 1992; Graham and Gottwald, 1992). Windbreaks have been used in Argentina since the 1970s for canker management (Muraro et al., 2001) and less citrus canker incidence has been observed in groves surrounded by tree windbreaks (Leite and Mohan, 1990).

In Australia, cadaghi windbreaks also served as a refuge for a predatory mite (*A. victoriensis)* when pesticide was applied in citrus orchards (Smith and Papacek, 1991). Cadaghi also did not serve as an alternative host for citrus thrip (*Scirtothrips aurantii*) in South Africa. Using cadaghi for citrus windbreaks controlled mites and thrips and reduced spraying (Grout and Stephen, 1995).

Site quality is an important factor when considering economically important species in windbreaks that yield marketable byproducts. Semi-permeable (1.5 m inter-tree distance) and dense (0.6 m inter-tree distance) poplar windbreaks in a high quality sites reached 100 m of protected area between 7 and 15 years whereas the ones with the same configuration in low quality sites reached 100 m of protected area between 25 and 35 years. Trees in low quality sites reached the peak of maximum diameter growth earlier than ones in high quality sites (Peri and Bloomberg, 2002).

Competition and Crop Yield

One pertinent windbreak issue is competition with the protected crop. Trees compete with the crop for light, water and nutrients, and planting highly competitive species in windbreaks reduces yield near the windbreak. Competition is usually greatest between 1H and 2H and decreases with distance from the windbreak. In Argentina, windbreak competition with crops and lack of convincing evidence of economic return slowed windbreak adoption (Peri and Bloomberg, 2002), suggesting that detailed economic analysis is an integral part of windbreak assessment. Growers implement windbreaks when the benefits overcome the losses from competition and space occupied by the windbreak.

Change in microclimate affects crop physiological processes and thus growth. Windbreaks reduced evaporation from bare soil by 20% and crop transpiration by less than 4% (Cleugh, 2002). In Australia, seeds in the quiet zone germinated earlier than in other areas, and crops in the competition zone matured early. Both aboveground biomass and grain yield within 3H was consistently less compared to areas further away from the windbreak. However, in drier years windbreaks reduced evaporative demand and increased grain yield up to 16-30% between 3-20H (Sudmeyer and Scott, 2002b). Both average strawberry (*Fragaria* spp.) production and total yield was highest at 1.2H from a dense poplar windbreak (3.2 m tall and < 15% porosity) in Argentina, but were lowest at 8.8H (Peri et al., 1998). Fast-growing tree windbreaks of *Eucalyptus, Callistemon* and *Melaleuca* species were effective as early as 30 months and increased potato growth and yield. Overall production increased by 7.7%, and yield was higher closer to the windbreaks (Sun and Dickinson, 1997). However, competition for water and nutrients, shading by windbreak trees and effects of phytotoxins reduced yield near windbreaks (Kort, 1988, Ong and Huxley, 1996). In the Philippines, nine-month-old cadaghi reduced growth of cabbage planted near the trees by shading and competing for moisture. More than 85% of tree roots were present in the top 30 cm of soil, and some of the roots extended beyond 0.5 m from the tree (Nissen et al., 1999).

Different crops require different types of windbreaks for optimum protection because of the variable final products and their variable levels of sensitivity to wind. Crops with final product growing underground such as garlic (*Allium sativum*) were resistant to wind damage. Crops such as cherry (*Prunus avium*) and strawberry were very sensitive (Peri and Bloomberg, 2002). Strong wind reduced flowering, increased flower shedding, reduced pollination and increased endosperm abortion in cherry. It also reduced the number of pollinators in spring, such as bees. Wind scarring was the major defect in cherry fruits, which reduced fruit quality. Better quality fruits were observed near the windbreak and decreased with distance from the windbreak (Peri and Bloomberg, 2002). Similar results were observed in New Zealand where weight of better quality kiwifruit (*Actinidia chinensis*) per vine decreased with distance from the windbreak because of scarring (McAneney et al., 1984). Semi-permeable poplar windbreaks with porosity less than 15% and dense windbreaks with 40% porosity increased gross cherry income by 8.8% and 17%, respectively (Peri and Bloomberg, 2002).

Root Distribution and Management

Root management is a major challenge in agroforestry systems when tree and crop roots compete for space, essential nutrients and water (Jose et al., 2004). Water and nutrient intake by plants largely depends on root length density as plants usually exploit nearby water and nutrients. Such resources were generally less near the trees and decreased with increasing root density (Sudmeyer, 2002). Information on windbreak root variables such as root density, lateral extent, distribution with depth and root length density (L_V) is critical to effectively manage competition. However, such information is rarely available and challenging to obtain because of the complex and variable root architecture, non-uniform distribution and the opaque soil (Bengough et al., 2000).

Auger sampling is one of the best methods for quantifying root diameter, length and biomass. However, a large sample size is required for better estimation. Core diameter is critical, and the number of replicates needs to be increased with decreasing core size diameter (Oliveira et al., 2000). Complete excavation of root systems is the best method to study roots but requires more time and is labor-intensive. The soil core-break method (Böhm, 1979; Escamilla et al. 1991; Oliveira et al., 2000) and the soil trench wall method (Böhm, 1979; Noordwijk et al., 2000) are two other common methods used for evaluating plant root distribution with depth. In the core-break method, soil cores are extracted, and roots are obtained by washing the soil. Roots thus obtained are used to estimate root length density (length of root per unit volume of soil, L_V) and/or weight per soil volume. On the other hand, the trench method gives the number of roots (N) per area of soil trench wall. All methods described above are destructive and do not provide an opportunity to re-measure the same root.

Minirhizotrons are a non-destructive method to monitor roots continuously and allow repeated measurement of roots for assessing root dynamics such as growth, biomass, branching and longevity (Smith et al., 2000b; Jose et al., 2001; Crocker et al., 2003).

Several factors determine the extent of root growth, frequency, architecture and distribution. Soil water content was one such factor. In Tasmania, both *E. nitens* and *E. globulus* continually irrigated since establishment had lower L_V compared to ones subjected to drought. Compared to larger diameter roots, smaller diameter roots had significantly greater L_V in both species. Root frequency was higher in drought treatment (Moroni et al., 2003). Water availability also regulated root and shoot growth in plants and determined the relative allocation of biomass. Trees in irrigated plantations had lower root weight compared to shoot weight since surface roots easily accessed water and nutrients (Fabião et al., 1995). Plants developed extensive root systems throughout the soil profile when available water fluctuated (Nepstad et al., 1994), but less extensive root systems when water was abundant (Matthes-Sears and Larson, 1995). Drought stress stimulated root growth (Comeau and Kimmins, 1989; Hamblin et al., 1990; Korotaev, 1992).

Root distribution also varied across soil types and profiles, and compact soil layers regulated plant root distribution (Bengough et al., 2000). In Australia, most *Pinus pinaster*, *P. radiata*, *E. kochii* and *E. globulus* roots were concentrated in the upper meter of the soil profile and generally decreased with increasing depth. The decrease in root number was gradual in top sandy layer but was abrupt in clayey subsoil. Clayey subsoil beneath the sandy layer acted as a barrier preventing root growth in the subsoil, resulting in higher L_V at the interface. Accumulation of nutrients and water at the interface also promoted this distribution pattern (Sudmeyer, 2002). Spacing between trees was another variable that determined spatial distribution of roots. When trees were planted closer, roots tended to avoid competition by growing away from the area (Brisson and Reynolds, 1994).

Genotype also regulated root development and distribution in plants. Rooting was significantly different among cashew (*Anacardium occidentale*) genotypes, with poor rooting in some and superior rooting in other genotypes (Aliyu, 2007). Among two olive cultivars, clonal Leccino cultivar had significantly higher rooting percentage and root production than in Leccio del Corno cultivar (Bartolini et al., 2008). In a silvopastoral system in New Zealand, clonal radiata pine (*P. radiata*) had significantly greater fine root length density than seedling trees. Clonal trees also had more extensive root system in the upper 10 cm of soil (Gautam et al., 2002).

Fine roots comprised most of the root system in species such as *P. pinaster*, *P. radiata*, *E. kochii* and *E. globulus* and were more than 90% of the total number of roots (Sudmeyer et al., 2004). Significantly higher smaller diameter roots were in the upper soil layer than in the deeper layer (Moroni et al., 2003). In the Congo, fine root density was higher in surface soil and significantly decreased with depth in *Eucalyptus* spp. planted in sandy soil. There was a marked decrease in root density with depth (Laclau et al., 2001). In plantations, more roots in the surface soil enhanced nutrient uptake and reduced nutrient loss in deep drainage. This was an advantage for trees growing in nutrient-poorer soils and increased biomass production (Laclau et al., 2001). Root density and L_V also differed among species (Jones et al., 1998; Knight, 1999; Sudmeyer, 2002; Sudmeyer et al., 2004).

Belowground competition between windbreak trees and crops can be minimized in several ways. One way is to select trees that have limited lateral root growth or are more deeply rooted than the crops. Species such as *E. kochii* which had the greatest lateral extent of roots relative to height can be more competitive than other taller trees with lesser lateral root extents such as *P. pinaster, P. radiata* and *E. globulus* (Sudmeyer et al., 2004). Another way to reduce belowground competition is by pruning tree roots. This can be effective in reducing competition from roots extending into the field (Jose et al., 2000; Sudmeyer et al., 2002b). In some species with positive correlation between horizontal root extension and tree height, root pruning is essential (Sudmeyer, 2002), especially in fast-growing species such as eucalypts and poplars. When lateral windbreak roots were pruned at 0.5H, crop yield increased from 61 to 81% (Sudmeyer et al., 2002a). Soybean production increased by 31% at 7.5 m in Nebraska when Siberian elm (*Ulmus pumila*) and poplar roots were pruned (Rasmussen and Shapiro, 1990). In Kenya, branch pruning of an *Acacia saligna* hedgerows significantly decreased L_V up to a distance of 2 m from the hedgerow (Peter and Lehmann, 2000).

Root pruning can only be effective in species such as poplars that have most of their roots in the top soil layer. Competition could be reduced by shallow ditches between the windbreak and the crop (Peri and Bloomberg, 2002). However, root pruning was expensive and difficult in deep-rooted species. Competition can be reduced only for few years, and long-term reduction becomes impossible in species such as *P. pinaster, P. radiata* and *E. globulus* which had the ability to regain both the lateral extent and vertical distribution of roots similar to the level before pruning within 2-4 years of pruning (Sudmeyer, 2002; Sudmeyer et al., 2004). Competition reduction is also challenging in eucalypts in which vertical roots changed direction and grew horizontal (Knight, 1999). The presence of deeper roots and growth of roots into the pruned zone from deep unpruned roots makes root pruning ineffective and expensive.

Biomass Accumulation and Carbon Sequestration

Increased carbon in the atmosphere has drawn worldwide attention and has become a major challenge to industrialized nations. Industrialization, increasing fossil fuel consumption and population increase are continuously adding greenhouse gases and CO_2 in the atmosphere. About 3.5 Pg (Pg = 10^{15} g) of carbon was deposited in the atmosphere every year primarily from burning fossil fuels and conversion of tropical forests to agricultural lands (Paustian et al., 2000). In an effort to reduce this level, participating countries in the United Nations Framework Convention on Climate Change (UNFCCC) in 1997 in Kyoto, Japan, agreed to lower greenhouse gas emissions by 5% or more below the 1990 level by 2012 through a treaty, widely known as Kyoto Protocol. The United States, one of the participants in the convention, emits about 25% of global carbon. However, the task became challenging after the US withdrew from the treaty in 2001. Nations are still looking for effective methods to reduce carbon emission and remove CO_2 from the atmosphere.

The earth's biosphere acts as both source and sink of atmospheric CO_2. About 30% of the newly added atmospheric carbon was removed by earth's biosphere between 1980 and 1995 (Houghton, 2000; Apps, 2003). One of the effective methods for reducing atmospheric carbon is to use trees. Trees take CO_2 from atmosphere and incorporate it into biomass. Therefore, reforestation of degraded sites and old farmlands is an efficient way to naturally sequester carbon. Compared to other plants (such as crops), trees have greater potential as they accumulate and store carbon for a longer period. However, trees utilized more CO_2 during initial growth than in longer term (Oren et al., 2001). Carbon is also stored in soil in the form of roots, litter and organic matter. However, only a small fraction of CO_2 fixed during photosynthesis enters the long-term storage; the rest is returned to the atmosphere again. Apart from carbon sequestration, carbon conservation and substitution are other ways to reduce atmospheric carbon (Bass et al., 2000). Carbon conservation includes activities related to the conservation of biomass and soil carbon, while carbon substitution includes conversion of biomass into durable products and increased biofuel use. Among these, carbon conservation has the greatest potential for rapid mitigation of climate change (Montagnini and Nair, 2004). Primary and secondary forests contain the largest biomass in tropical systems. Therefore, management of tropical forests and forests in other parts of the globe can sequester a significant amount of carbon through growth and biomass accumulation.

Quantification of carbon stored in forest biomass has become an important issue for national policies and international negotiations (Dixon et al., 1994). National forest inventories are widely used for estimating carbon stocks in forests. However, these do not give a complete picture of the carbon stock in forests as most inventories include only the merchantable volume and ignore seedlings and saplings (Vallet et al., 2006). Diameter at breast height (DBH) is the most commonly used and measured variable in large scale national programs. However, others have suggested using both DBH and height (Jenkins et al., 2003; Lambert et al., 2005). Height was a secondary variable for stem biomass estimation (Lambert et al. 2005), and including height added precision to the estimate (Joosten et al., 2004; Lambert et al., 2005; Vallet et al., 2006, Zhou et al., 2007). Therefore, both DBH-based and DBH- and height-based equations are often developed and used. But measuring height in natural forests can be challenging and costly as tree tops are difficult to see. DBH was an essential variable for estimating crown biomass but height was less applicable (Lambert et al., 2005). In volume calculations, using both diameter and height took into account the recent growth (Vallet et al., 2006). DBH has also been used indirectly in the form of stem cross sectional area (SCSA) at 1.3 m in prairie shelterbelts in Canada. SCSA was the best predictor for aboveground biomass in deciduous and coniferous species, and including height did not improve the relationship. In the case of shrubs, shelterbelt volume (product of height, width and length) was the best biomass predictor (Kort and Turnock, 1999).

Agroforestry is a potential carbon sink for mitigating the increasing carbon in the atmosphere (Albrecht and Kandji, 2003). Nair et al. (2009) estimated approximately 1,023 million ha of land under agroforestry worldwide. Additionally, 630 million ha of unproductive croplands and grasslands could potentially be converted to agroforestry (IPCC, 2000). If trees are used and judiciously managed, agroforestry can become efficient and can store a significant amount of carbon. While carbon sequestered and stored in agroforestry systems is less compared to forests, particularly primary and secondary forests in the tropics (Duguma et al., 2001; Schroth et al., 2002; Montagnini and Nair, 2004), they have the potential to reduce pressure on natural forests for wood products and can increase agricultural yield at the same time. Among different agroforestry practices (riparian forest buffers, windbreaks, alley cropping, silvopasture, forest farming and special applications), windbreaks and riparian forest buffers are planted for their long-term benefits and are not easily and quickly replaced by other practices (Schoeneberger, 2009). Thus, the carbon sequestered by these agroforestry practices remains in biomass for a longer period.

Because of the fertile soil, trees in agroforestry systems usually grow faster and produce higher biomass. Incorporating multiple species increases nutrient use, and mixed species planting therefore can more efficiently sequester carbon. Both trees and crops remove CO_2 from the atmosphere as they grow and incorporate it in their biomass. More than half of the carbon sequestered by trees is stored in the soil through root growth, turnover, root exudates and litter decomposition (Montagnini and Nair, 2004).

Carbon sequestration potentials of tropical agroforestry systems was estimated between 12 and 228 Mg ha^{-1} (Mg = 10^6 g) (Albrecht and Kandji, 2003). In aboveground components, carbon sequestration potential of agroforestry systems was estimated to be 2.1 x 10^9 Mg C $year^{-1}$ in the tropics and 1.9 x 10^9 Mg C $year^{-1}$ in temperate regions (Oelbermann et al., 2004). Carbon sequestration ranged between 0.3 and 15.2 Mg ha^{-1} y^{-1} in the aboveground plant parts and between 1.3 and 173 Mg ha^{-1} in soil in various agroforestry systems across the globe (Nair et al., 2009). Nair and Nair (2003) estimated that agroforestry in the US alone has the potential to sequester 90.3 Tg C yr^{-1} (Tg = 10^{12} g) by the year 2025. Agroforestry systems stored 9, 21, 50 and 63 Mg C ha^{-1} on average in semiarid, subhumid, humid and temperate regions, respectively (Schroeder, 1994).

Approximately 115,000 ha of windbreaks were needed in the continental US alone (Brandle et al., 1992). Besides modifying microclimate and protecting crops, windbreaks can provide other functions, including carbon sequestration. Windbreak carbon sequestration depends on soil texture, age, location and windbreak condition (Kort and Turnock, 1999). Estimates show that cropland with windbreaks in Nebraska could sequester approximately twice the amount of CO_2 as cropland without windbreaks. Field windbreaks planted in 5% of the cropland could sequester between 11.7-23.4 metric tons of CO_2 in 20 years and twice the amount in 40 years (Schoeneberger, 2009). In Canada, 32 t C/km was estimated in aboveground parts in green ash (*Fraxinus pennsylvanica*), 105 t C/km in hybrid poplar, 41 t C/km in white spruce (*Picea glauca*), and 26 t C/km in caragana (*Caragana arborescens*) in prairie shelterbelts (Kort and Turnock, 1999). Field windbreaks planted in 5% of the approximately 85 million ha of unprotected cropland in the North Central US alone could sequester over 215 Tg CO_2 in aboveground plant parts in 20 years. Farmstead windbreaks around 300,000 unprotected farms could sequester 13 Tg of CO_2 in the same period (The USDA National Agroforestry Center, http://www.unl.edu/nac/workingtrees.htm). Zhou et al. (2007) estimated aboveground weights of various aged Russian-olive (*Elaeagnus angustifolia*) trees in windbreaks in Montana between 1,744 and 4,957 kg/100 m windbreak length. Assuming 50% of the plant biomass is C (Gifford, 2000), these windbreaks stored between 872 and 2,479 kg C/100 m windbreak length. More carbon could be sequestered by using fast-growing species in windbreaks (Kort and Turnock, 1999).

Despite their carbon sequestration potential, agroforestry practices were not explicitly accounted for in the Forest Inventory Analysis of the US Forest Service and the Natural Resources Inventory of the USDA Natural Resources Conservation Service

(Perry et al., 2005). Agroforestry practices were also not included in many greenhouse gas mitigation reports (Schoeneberger, 2009).

In summary, well designed windbreaks can mitigate most wind related agricultural problems such as soil erosion and crop damage. Windbreaks can increase crop yield by modifying microclimate and increase crop quality by reducing wind damage. However, competition between windbreak trees and crop is a major issue as it reduces crop yield at the windbreak-crop interface. Therefore, species that produce deep roots or have limited lateral roots should be selected to minimize competition. While mitigating wind related agricultural issues, trees in agroforestry systems sequester carbon and store in biomass.

CHAPTER 3
SINGLE-ROW WINDBREAK FUNCTION AND ITS EFFECT ON MICROCLIMATE ON THE LEESIDE

Introduction

Physical damage to crops and nutrient loss through soil erosion are problematic to growers in agricultural systems where strong winds are common, especially when the soil is sandy and the top soil contains nutrients. Wind transported soil contained more nutrients than the field soil from which it is removed (Nuberg, 1998; Sudmeyer and Scott, 2002a). Strong winds also reduced flowering, increased flower shedding, reduced pollination and increased endosperm abortion in some fruit trees such as cherry (*Prunus avium*) and decreased the number of pollinators such as bees (Peri and Bloomberg, 2002). Factors such as these can lead to a reduction in productivity and pose a serious threat to a growers' ability to be economically viable in Florida.

Florida is the major citrus producer and one of the leading vegetable producers in the US. Both crops are profitable, generating ~$20 billion annually. Florida agriculture products were distributed to the US and exported to 140 countries across the globe (FDACS, 2008). However, diseases in citrus, impact of high winds (including tropical storms and hurricanes), and freezes during cold fronts threaten these industries.

Citrus canker (*Xanthomonas campestris* pv. *citri*) is a prevailing disease and is caused by a bacterium. It is spread by wind-driven rain. Its spread increases during tropical storms and hurricanes. A canker eradication program was active until the end of 2005. Infected trees were removed, and all trees within a 579 m (1,900-foot) radius of an infected tree were mandatorily destroyed. Because of the extensive canker spread in the 2004/05 hurricane seasons, eradication of canker became infeasible, and the USDA deactivated the rule in January 2006. Since then, canker control efforts have shifted to canker management.

Windbreaks are commonly used in South America for canker management (Leite and Mohan, 1990; Gottwald and Timmer, 1995; Behlau et al., 2008) and worldwide to reduce the impact of high winds (Jones and Sudmeyer, 2002; Peri and Bloomberg, 2002; Sudmeyer and Scott, 2002a; Brandle et al., 2004; Sudmeyer and Flugge, 2005). They are also an important component of integrated citrus management (Leite, 2000; Behlau et al., 2008), and citrus growers in Florida are beginning to follow the same practices and are introducing tree windbreaks.

Well designed windbreaks located perpendicular to the direction of prevailing wind have many benefits. They increase both crop and livestock production, reduce soil erosion and physical damage to crops, provide shelter for structures and livestock, and improve microclimate and irrigation efficiency. Windbreaks also reduced evaporative demand in extremely dry years (Sudmeyer and Scott, 2002b) and increased crop nitrogen uptake by modifying microclimate (Shah and Kalra, 1970). Windbreaks were profitable where strong winds damage crops (Jones and Sudmeyer, 2002). Although the current demand for tree windbreaks in Florida is from citrus growers, vegetable growers who have been using grass species such as ryegrass (*Lolium* spp.) and sugarcane (*Saccharum* spp.) for decades can also benefit from tree windbreaks.

Established windbreaks of native tree species such as redcedar and pines are present in some areas of Florida. But due to the urgency of controlling the spread of citrus canker, citrus growers are also using non-native, fast-growing species such as cadaghi (*Corymbia torelliana*) and other eucalypts (*Eucalyptus* spp.). Cadaghi is highly suitable for windbreaks (Sun and Dickinson, 1997) and preferred by growers because of its fast growth, dense canopy, branch retention, and evergreen nature. Field observations suggest that it can produce effective windbreaks as early as 2-3 years. It is now widely planted for citrus windbreaks in Florida (Rockwood et al., 2008), mostly in single rows. However, the function of single-row fast-growing tree windbreaks and other species windbreaks in Florida needs to be studied.

The study was conducted in south Florida to a) examine extent of wind reduction and b) study spatial and temporal effects on microclimate on the leeside of the windbreaks. The hypothesis was that the single-row tree windbreaks of eastern redcedar and cadaghi reduce wind and modify microclimate on the leeside.

Materials and Methods

Study Areas

The study was conducted at Southwest Florida Research and Education Center/University of Florida (SWFREC/UF, 26°27'46"N, 81°26'04"W) at Immokalee and C&B Farms (26°27'30"N, 80°58'46"W) near Clewiston, Florida. The sites are ~48 km apart, but both have similar climates. In 2008, the absolute monthly minimum temperature at SWFREC was -0.4 °C in January, and monthly maximum was 35.1 °C in June (Florida Automated Weather Network, http://fawn.ifas.ufl.edu/). Prevailing wind direction was from the east.

SWFREC has a single-row eastern redcedar windbreak on its northern boundary (Table 3-1). Single-row cadaghi windbreaks at C&B Farms were planted along primary irrigation channels, with ~1.5 m between the windbreaks and the channels. Access roads separated windbreaks and crop fields in most places, but some windbreaks were planted at the ends of fields. East-west oriented windbreaks were planted approximately every 300 m, while the distances between north-south oriented windbreaks ranged between 480-680 m. Sugarcane windbreaks were planted parallel to north-south oriented windbreaks (between two east-west oriented windbreaks) and bordered ~0.9 ha blocks. The oldest cadaghi windbreak was planted in 1988, while the rest were planted in subsequent years. Some windbreaks were established and functional while others were in the early stages of growth. Three established windbreaks (WB) were selected for the study (Table 3-1, Figure 3-1). WB1 was east-west oriented on the northern boundary of C&B Farms. WB2 was ~300 m south of WB1. WB3, the easternmost windbreak, was oriented north-south. Porosities of redcedar, WB1, and WB3 were uniform throughout the height of the windbreak. However, pruning of lower branches created some large gaps near the ground in WB2.

Table 3-1. Number of trees (n), age (years), height (m), diameter at breast height (DBH, cm), porosity (%), live crown length (m) and spacing between trees (m) of windbreaks used in the microclimate study (mean value ± standard error).

Windbreak	Age	Height	DBH	*Porosity	Crown length	Spacing
SWFREC/UF:						
Redcedar (n=114)	20	7.3±0.1	14.6±0.5	17.4±0.9	7.0±0.1	1.2±0.1
C&B Farms:						
Cadaghi WB1 (n=64)	20	17.5±0.2	40.6±1.2	22.1±1.5	13.6±0.3	2.5±0.1
Cadaghi WB2 (n=51)	8	10.3±0.2	24.6±0.7	36.3±2.0	9.3±0.2	4.9±0.1
Cadaghi WB3 (n=72)	6	8.0±0.1	17.9±0.4	28.7±1.6	7.2±0.2	3.3±0.1

Measured in December 2007; *n=5.

Methods

Five windbreak sections (~25 m long) were randomly selected in the redcedar windbreak at SWFREC. In the windbreaks at C&B Farms, five sections (~45 m long) were selected in each windbreak. Total height, diameter at breast height (DBH), live crown length (length from the lowest live branch to the top of the tree) and spacing between trees were measured for each tree in the windbreak sections (Table 3-1).

Pictures of randomly selected windbreak sections were used to estimate windbreak porosity using Kenny's (1987) digitizing method. In this method, pictures of windbreaks are digitized and converted to black and white pictures. Black and white pixels are then counted using digitizing software and porosity is calculated as the ratio of white to total pixels of the black and white picture.

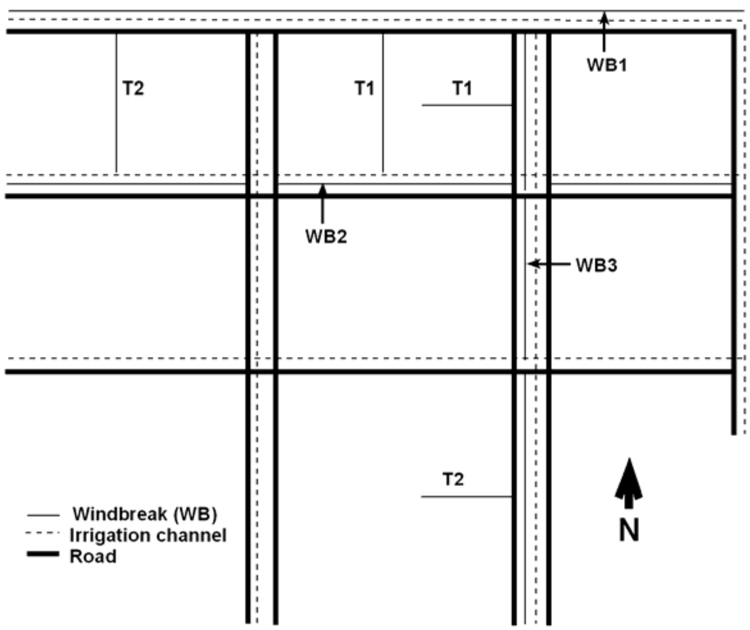

Figure 3-1. Relative position of study windbreaks at C&B Farms and location of transects (T) where automated weather stations were installed.

Automated weather stations (AWS) were installed at two times the windbreak height (2H), 6H, 10H, and 14H along two separate transects perpendicular to the windbreak on the south side of redcedar windbreak at SWFREC between January and June 2008. At C&B Farms, AWS were installed in November 2007 and measurements were taken until December 2008. Sugarcane windbreaks and crops in most part of the field were fully grown. There was open space only for a transect until mid-June 2008 where wind and microclimate was not influenced by sugarcane windbreaks. Therefore, AWSs were installed only in a transect perpendicular to windbreaks WB1 and WB2.

After the crops were harvested and the sugarcane windbreaks were cut in June/July 2008, another transect was installed in July. AWS were installed at 2, 4, 6, and 10H from WB1. Another series of AWS were installed at 2, 4, 6, and 8H from WB2 in the same transect. Stations at 10, 6, 4, and 2H from WB1 were approximately at 15, 23, 27, and 31H from WB2. Similarly, stations at 8, 6, 4, and 2H from WB2 were approximately at 13, 14, 15, and 16H from WB1. AWS were also installed at 4, 8, 12, and 16H on the west side of WB3 along two transects from July to December 2008.

At each station, wind speed, temperature and relative humidity (RH) were measured at a height of 2 m above the ground. Wind speed was measured using HOBO wind speed smart sensors (S-WSA-M003), and temperature/RH was measured using HOBO temperature/RH sensors (S-THA-M002). Automatic measurements were taken every 30 seconds until July and every 1-minute after that. Measurements were recorded in HOBO Micro Station Data Loggers (H21-002). A control station located away from the windbreaks at each site also measured temperature/RH, and wind speed and direction at 2 m above the ground using wind speed and direction smart sensors (S-WCA-M003). Control stations were located 266 m (38H) and 531m (59H) from the windbreaks at SWFREC and C&B Farms, respectively.

Data Analysis

Hourly averages were computed from the recorded data. Readings from two transects were also averaged for each location when available. However, data recorded at 1-minute intervals on August 19, 2008 were also used to study the patterns and extent of wind reduction during tropical storm Fay. Measured wind speed, temperature, and RH on the leeside of the windbreak were divided by the open (control station) wind speed, temperature, and RH during that interval, respectively, to get relative values.

Data were filtered by wind direction and used in the analysis only when the wind direction was between 0 and 180 degrees to the windbreak. Therefore, only the measurements when wind direction was between 270 and 90 degrees were considered for redcedar and cadaghi (WB1) windbreaks. For cadaghi windbreaks WB2 and WB3, only the measurements between wind directions of 180 to270, and 0 to 180 degrees, respectively, were considered. Separate averages were calculated for range of wind speeds and directions, and plotted to study the pattern in wind reduction during the period. Time series plots were also used to examine extent of wind reduction and patterns in microclimate modification on the leeside of the windbreaks. Weather was considered normal when the temperatures in the open were greater than 10° C. Temperatures below 10° C in the open was considered a cold front. For temporal variation in temperature and RH, times between 7AM and 7PM was considered day and between 7PM and 7AM were considered night. It was not possible to plot data from all measurement locations. Only the data from extreme locations are presented in some cases to make the time series plots legible. As sugarcane windbreaks were tall by the end of August 2008, and influenced measurements, only data up to August were used.

Results

Wind Reduction

At SWFREC, 1-hour average maximum wind speed was 8.1 m/s during the study period. On the south side of the redcedar windbreak, wind at all measurement locations was lower than in the open when the wind direction was between 0 and 180 degrees to the windbreak (Figure 3-2 and 3-3). Regardless of wind speed and wind direction, wind reduction showed a similar pattern, with minimum wind speed at 2H and gradual increase at locations further away from the windbreak. Maximum wind was always recorded at 14H. Relative wind speed at 2H was approximately 18% when wind direction was between 45 and 135 degrees to the windbreak (Figure A-1). Regardless of wind direction, wind reduction at 2H was at least 64% and at 14H was at least 22%. Wind generally was not detected at 2H when the open wind speed was less than 2.5 m/s.

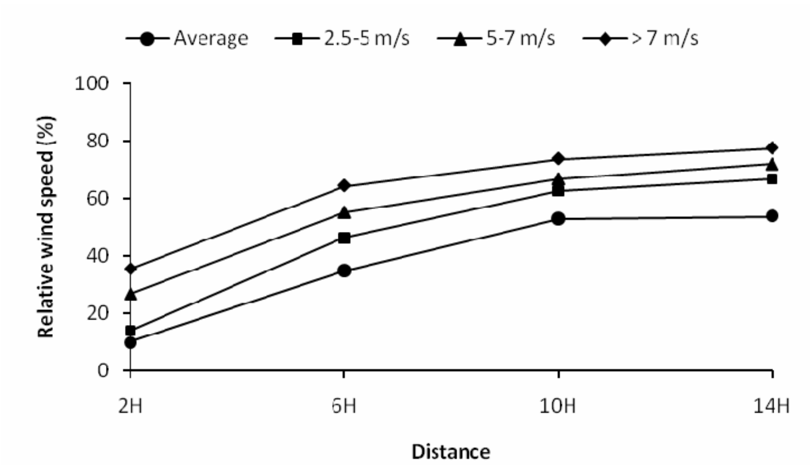

Figure 3-2. Average relative wind speeds at different distances on the south side of eastern redcedar windbreak at SWFREC during various wind speeds when the wind direction was between 0 and 180 degrees to the windbreak (Average = average relative wind speed during the study period).

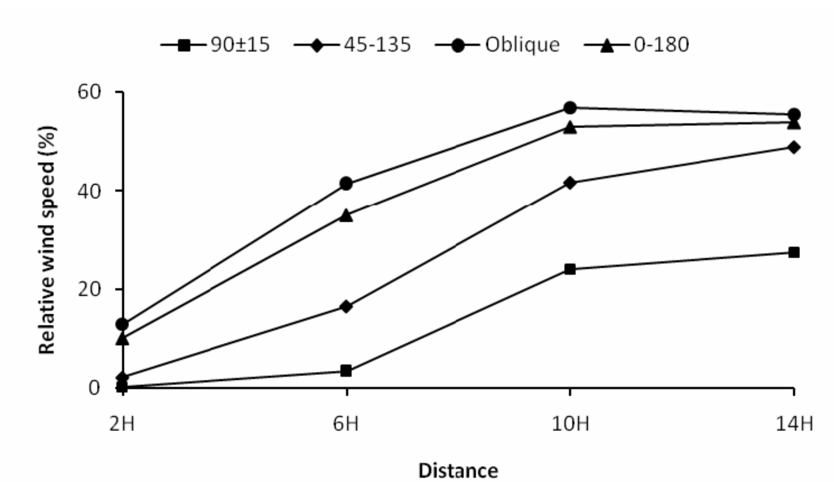

Figure 3-3. Average relative wind speeds at different distances on the south side of eastern redcear windbreakat SWFREC during various wind directions regardless of wind speed (Oblique: wind direction less than 45 and greater than 135 degrees to the windbreak).

Maximum wind reduction occurred when wind direction was perpendicular to the windbreak, regardless of wind speed (Figures 3-3, A-1 and A-2). When the wind direction was oblique (less than 45 and greater than 135 degrees), wind reduction at 2 and 14H was 88 and 55%, respectively. When direction was nearly perpendicular (90±15 degrees), wind reduction was 100 and 73% at 2 and 14H, respectively.

For the range of same wind speeds (wind speeds less than 5 m/s or greater than 5 m/s), more wind reduction was observed when the direction approached perpendicular to the windbreak (Figure 3-4). The reduction was 69% at 2H and 26% at 14H when the direction was less than 45 and more than 135 degrees to the windbreak, and wind speed was greater than 5 m/s.

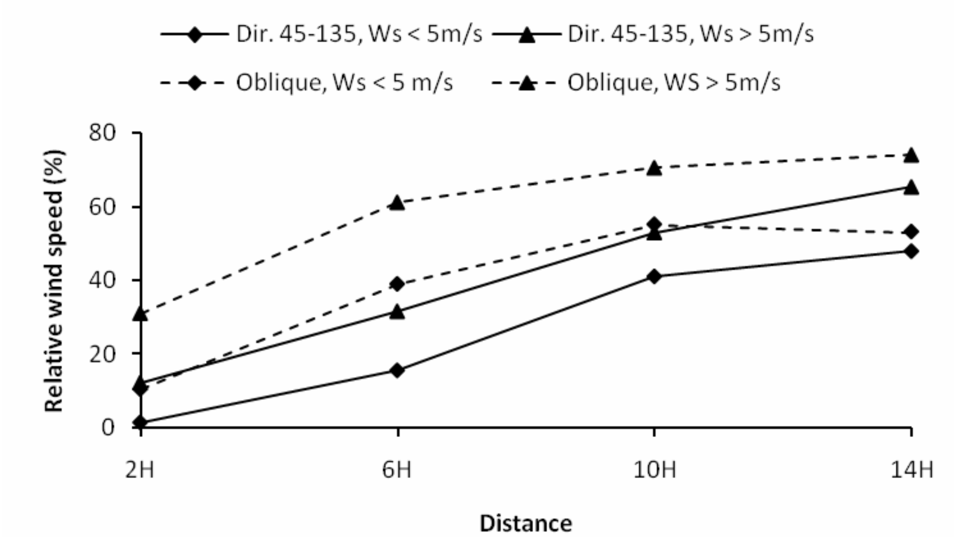

Figure 3-4. Relative wind speeds on the south side of eastern redcear windbreak at different distances when wind direction was oblique (less than 45 and greater than 135 degrees) and nearly perpendicular (between 45 and 135 degrees), and when wind speed was less or greater than 5 m/s.

At C&B farms, 1-hour average maximum wind speed was 7.6 m/s during the study period. Average wind speed on the south side of WB1 was always lower than in the open. As observed at SWFREC, more wind reduction occurred when wind direction was perpendicular to the windbreak regardless of wind speed (Figures 3-5 and A-3). Wind speed was generally less at 4H among all locations and gradually increased up to 10H, after which wind speed decreased at16H as it approached WB2. Highest relative wind speed of 50% was recorded at 10H. At other locations wind reduction was more than 50%. At 2H, wind reduction was at least 77%. Wind was detected at 2H even when the open wind speed was less than 1.5 m/s and wind direction was nearly perpendicular (90±15 degrees) to the windbreak.

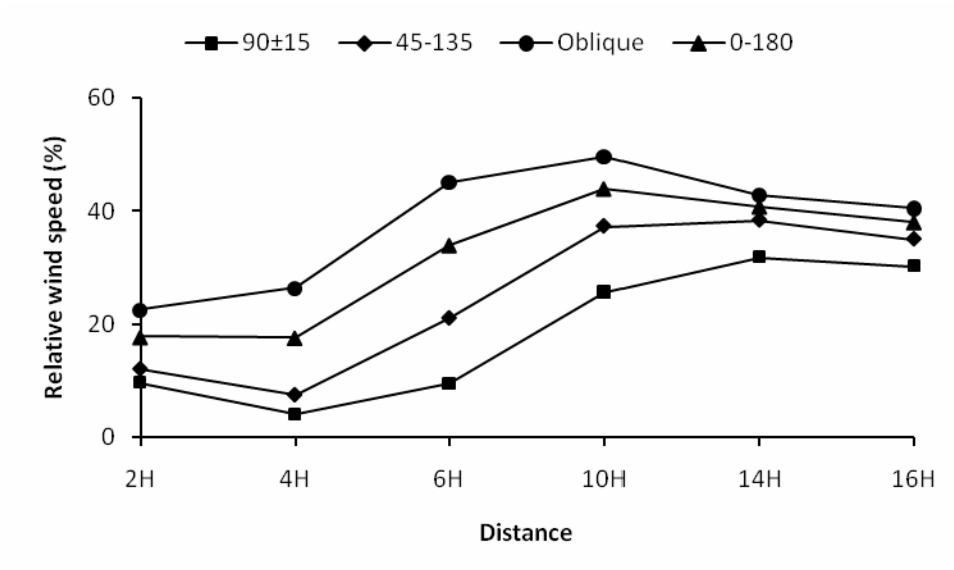

Figure 3-5. Average relative wind speeds at different distances on the south side of cadaghi windbreak (WB1) at C&B Farms during various wind directions regardless of wind speed (Oblique: wind direction less than 45 and greater than 135 degrees to the windbreak).

For wind speeds greater or less than 5 m/s, more wind reduction was obtained when the wind direction was perpendicular than oblique (Figure 3-6). Regardless of wind speed, minimum wind speed was recorded at 2H when the direction was oblique (less than 45 and greater than 135 degrees to the windbreak) to the windbreak and at 4H when the direction nearly perpendicular (between 45 and 135 degrees to the windbreak).

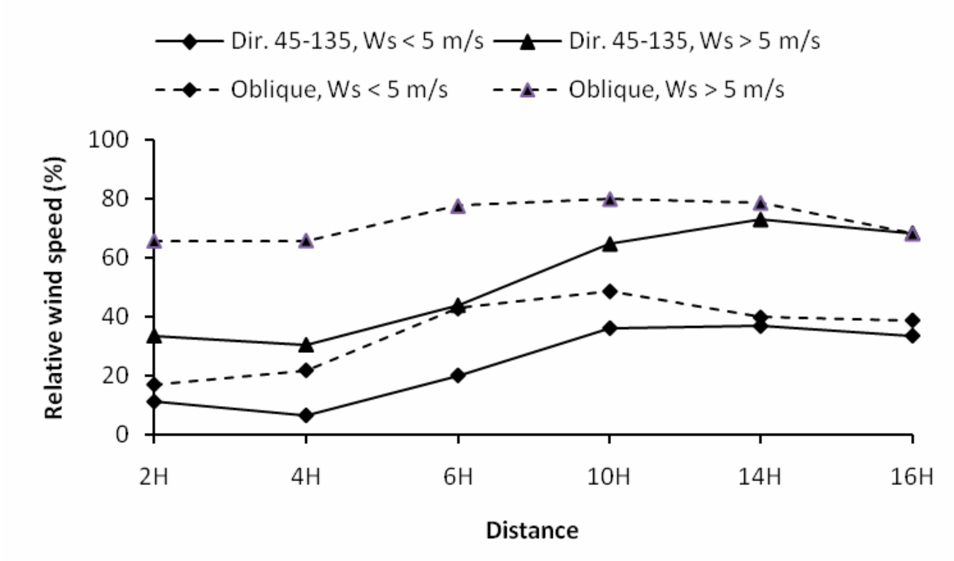

Figure 3-6. Relative wind speeds on the south side of cadaghi WB1 at C&B Farms when wind direction was oblique (less than 45 and greater than 135 degrees to the windbreak) and nearly perpendicular (between 45 and 135 degrees to the windbreak), and wind speed was less or greater than 5 m/s.

On the north side of WB2, maximum wind reduction was at 6H (78%) when the wind direction was between 45 and 135 degrees to the windbreak (Figures 3-7 and A-4). When the direction was oblique (less than 45 and greater than 135 degrees to the windbreak), maximum reduction was at 2H (at least 72%). During the study, maximum wind speed on the north side of WB2 was only 60% (at 23H) of the open wind regardless of direction. As observed on the south side of WB1, wind speed gradually increased at locations further away from the windbreak and decreased at 31H as it approached WB1.

For wind speeds greater or less than 5 m/s, highest wind reduction was observed when the direction was between 45 and 135 degrees to the windbreak (Figure 3-8). Wind reduction was 33% at both 15 and 23H when wind speed was greater than 5 m/s whereas the reduction was only 29% at 23H when the direction was less than 45 and greater than 135 degrees to the windbreak.

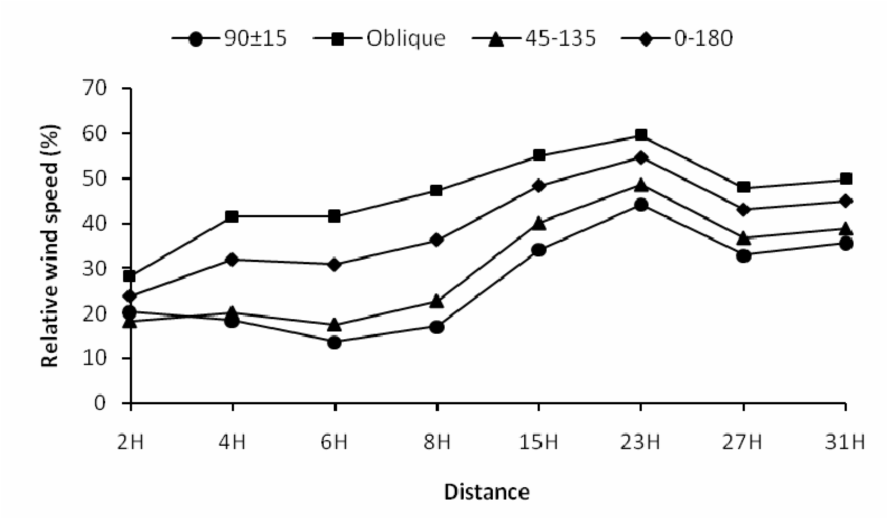

Figure 3-7. Average relative wind speeds at different distances on the north side of cadaghi windbreak WB2 at C&B Farms during various wind directions regardless of wind speed (Oblique: wind direction less than 45 and greater than 135 degrees to the windbreak).

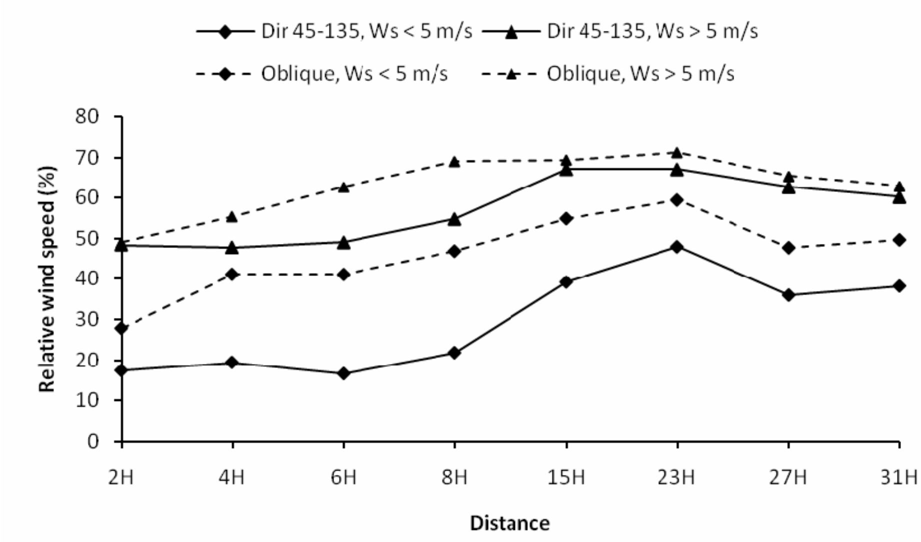

Figure 3-8. Relative wind speeds on the north side of cadaghi windbreak WB2 at C&B Farms when wind direction was oblique (less than 45 and greater than 135 degrees to the windbreak) and nearly perpendicular (between 45 and 135 degrees to the windbreak), and wind speed was less or greater than 5 m/s.

On August 19, 2008, tropical storm Fay passed through the Florida peninsula. Wind direction was East-Northeast early in the morning and gradually shifted to West by midnight. Wind direction remained between these two extremes throughout the day.

Open wind speed ranged between 2.8 and 13 m/s. Cadaghi windbreaks effectively reduced wind on the leeside during the storm (Figures 3-9 and 3-10).

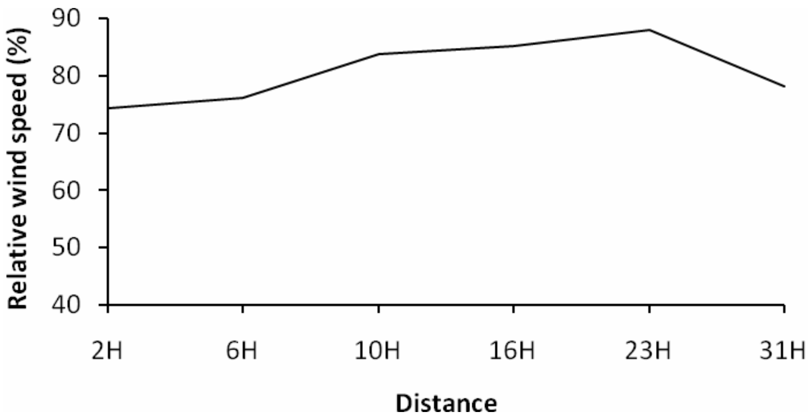

Figure 3-9. Average relative wind speed on the north side of cadaghi windbreak WB2 at C&B Farms during tropical storm Fay on August 19, 2008, when wind direction was between 0 and 180 degrees to the windbreak.

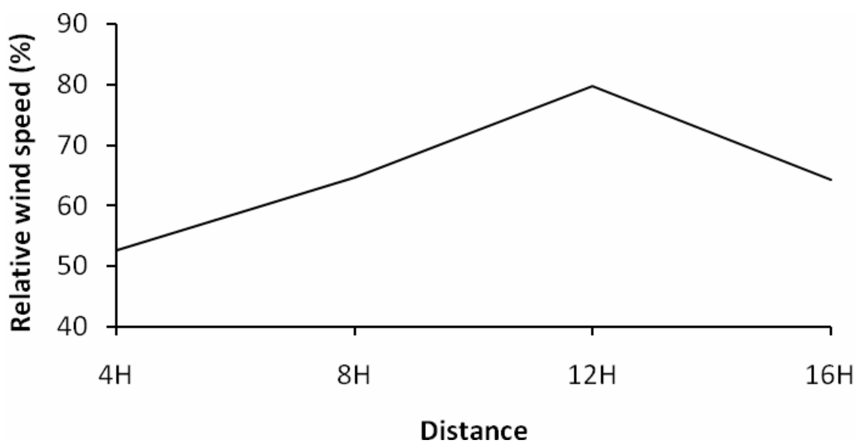

Figure 3-10. Average relative wind speed on the west side of cadaghi windbreak WB3 at C&B Farms during tropical storm Fay on August 19, 2008, when wind direction was between 0 and 180 degrees to the windbreak.

During the tropical storm, the average wind speeds on the north side of WB2 and west of WB3 were less than 90% and 80% of the open wind speed, respectively, when the wind direction was between 0 and 180 degrees to the windbreak (Figures 3-9 and 3-

10). Average wind speed was lowest at 2H on the north side of WB2 and at 4H on the west side of WB3. Due to WB1 at about 33H from WB2 and the sugarcane windbreak at about 20H from WB3, wind speeds at 31H from WB2 and 16H from WB3 were lower than at preceding locations.

Compared to the open, wind speed on the north side of WB2 was comparatively low most of the time with frequently higher wind speed (Figure 3-11). 2H and 6H had the lowest wind speeds when the direction was less than 45 and greater than 135 degrees, and between 45 and 135 degrees to the windbreak, respectively. Because of the large pores at the base of WB2, jetting effect was also observed on the leeside (Figure A-5). As the wind direction was usually perpendicular to the windbreak when wind speed was 7-9 m/s (Figure 3-11), wind speeds at all locations except 6H and 10H were at least 5% higher than in the open. However, when open wind was greater than 9 m/s (range: 9-13 m/s) and wind direction between 45 and 135 degrees to the windbreak, average wind speed was at least 10% lower at 23H than in the open.

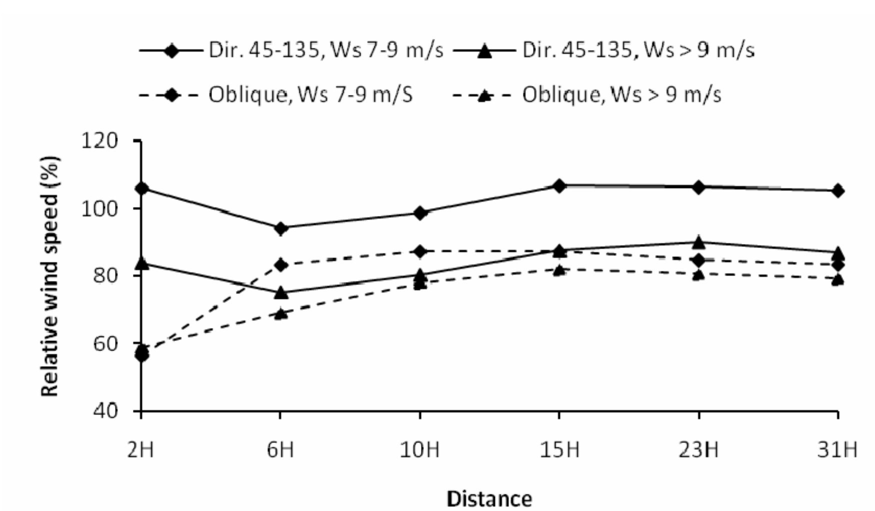

Figure 3-11. Wind speed on the north side of cadaghi windbreak WB2 at C&B Farms during tropical storm Fay on August 19, 2008 at various wind speeds and wind directions (Oblique: less than 45 and greater than 135 degrees to the windbreak).

On the west side of WB3, wind speeds at 4, 8, 12, and 16H were usually less than the open most of the time when the direction was between 0 and 180 degrees to the windbreak (Figure 3-12). Regardless of wind speed and direction, highest wind reduction occurred at 4H (at least 20%) and least at 12H (Figure 3-12 and Appendix A-6). When wind direction was oblique (less than 45 and greater than 135 degrees to the windbreak), wind speed at 12H was 10% higher than in the open. This was primarily because the wind direction was mostly between 160 and 178 degrees to the windbreak (~ parallel direction). When open wind speed was 12.3 m/s, maximum wind of 6.2 m/s was recorded at 12H, regardless of wind direction.

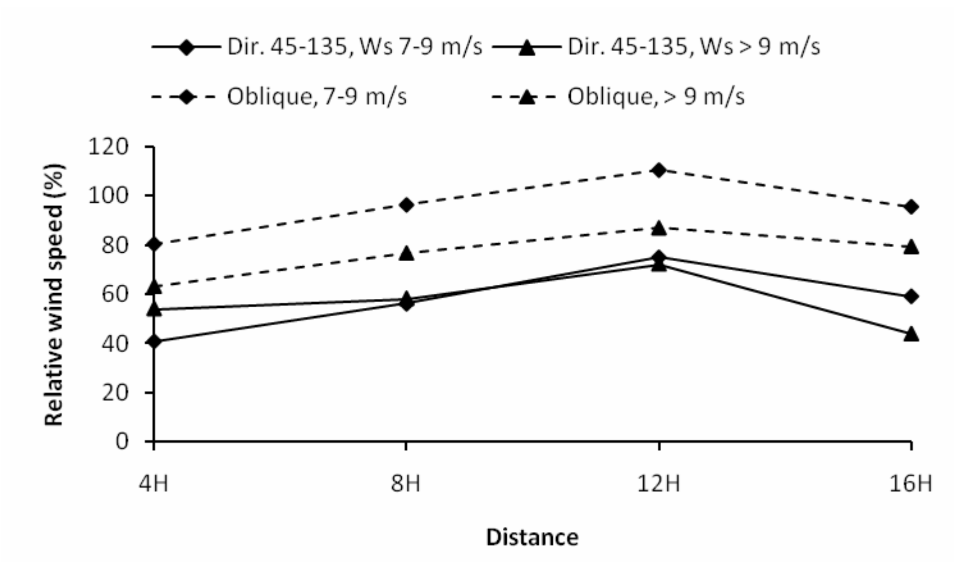

Figure 3-12. Wind speed on the west side of cadaghi windbreak WB3 at C&B Farms during tropical storm Fay on August 19, 2008 at various wind speeds and wind directions (Oblique: less than 45 and greater than 135 degrees to the windbreak).

Temperature Modification

Change in temperature on the leeside of the windbreaks was less compared to wind speed. During normal weather conditions, regardless of wind speed, nighttime temperature on the south of the redcedar windbreak was usually cooler at 2H (up to 1.5

°C) but warmer at 14H (up to 1.3 °C) compared to temperature in the open (Figure A-7). On average relative temperatures at 2H and 6H were approximately 1% lower and at 10H and 14H were 1% higher than in the open (not shown here). When the wind direction was between 0 and 180 degrees to the windbreak, and when open wind speed exceeded 3 m/s, temperatures on the south of the windbreak at all locations were similar to the temperatures in the open.

During the day, temperatures at all locations on the south side of the windbreak were usually higher than in the open (Figure A-8). Locations near the windbreak (2H and 6H) had higher temperatures most of the time compared to ones further away (10H and 14H) from the windbreak (Figures 3-13 and A-8). Temperature at 2H was up to 2.5° C warmer than in the open while it was up to 0.6° C at 14H. Average temperature at 2H was approximately 3% greater than in the open when the open wind speed was greater than 2.5 m/s.

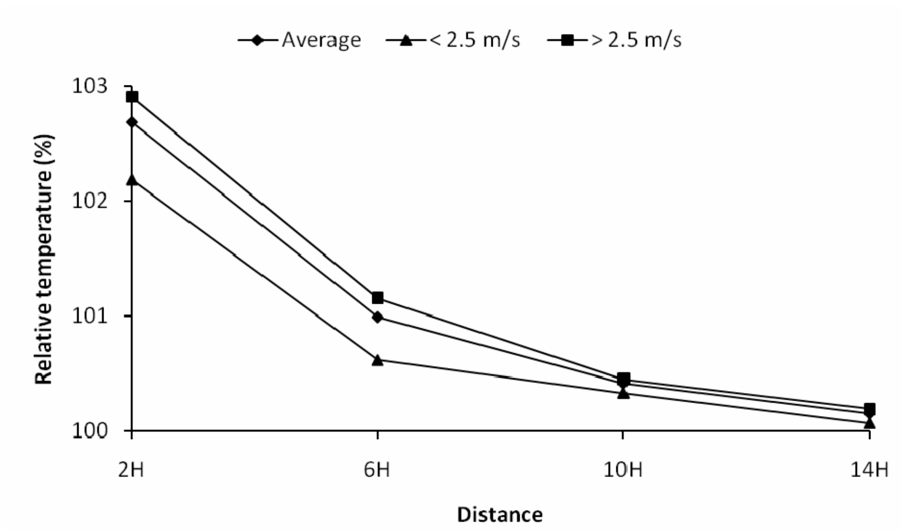

Figure 3-13. Daytime average relative temperature on the south side of the eastern redcedar windbreak at SWFREC at various wind speeds when the wind direction was between 0 and 180 degrees to the windbreak (Average: average of the study period regardless of wind speed).

At C&B Farms, nighttime temperatures at locations (2H and 16H) south of WB1 did not show any specific trend until the end of June, after which the measurements were usually lower than in the open (Figure A-9). Temperatures at locations further away from the windbreak (10H, 14H and 16H) were usually higher than in the open and slightly greater than at 2H and 6H. When the open wind speed was less than 2.5 m/s, relative temperature at 2H was similar to open and gradually increased up to 16H where it was 2% higher. When the open wind speed was greater than 2.5 m/s, relative temperature at 2H was approximately 2% and at 16H was 0.5% lower than in the open. Variation in nighttime temperature at the same location was higher until May and was less in later months (Figure A-9). Similar patterns were observed on the north side of WB2 when the wind was from south, except that the temperatures at all locations were slightly higher compared to the open (not shown here). Daytime temperatures at locations south of WB1 were also relatively higher than in the open. During the study, temperatures at 6H from WB1 were up to 2.9 °C higher than in the open. On average relative temperatures at 2 and 6H were 2% higher, where as it was 1% higher at 10, 14 and 16H.

During cold fronts, temperature modifications south of redcedar and cadaghi (WB1) windbreaks were similar. When wind speed was less than 2 m/s, temperatures at 2 and 6H south of redcedar windbreak were usually cooler than in the open and locations further away from the windbreak. Regardless of wind speed, temperature at 2H and 6H were up to 1 and 1.3° C lower than in the open, respectively. At C&B Farms, temperatures at 2 and 6H south of WB1 were up to 1.7 and 1.9° C lower than in the open, respectively (Figure 3-14). Temperatures at all locations were either equal or similar to the open when the open wind speed was greater than 2 m/s.

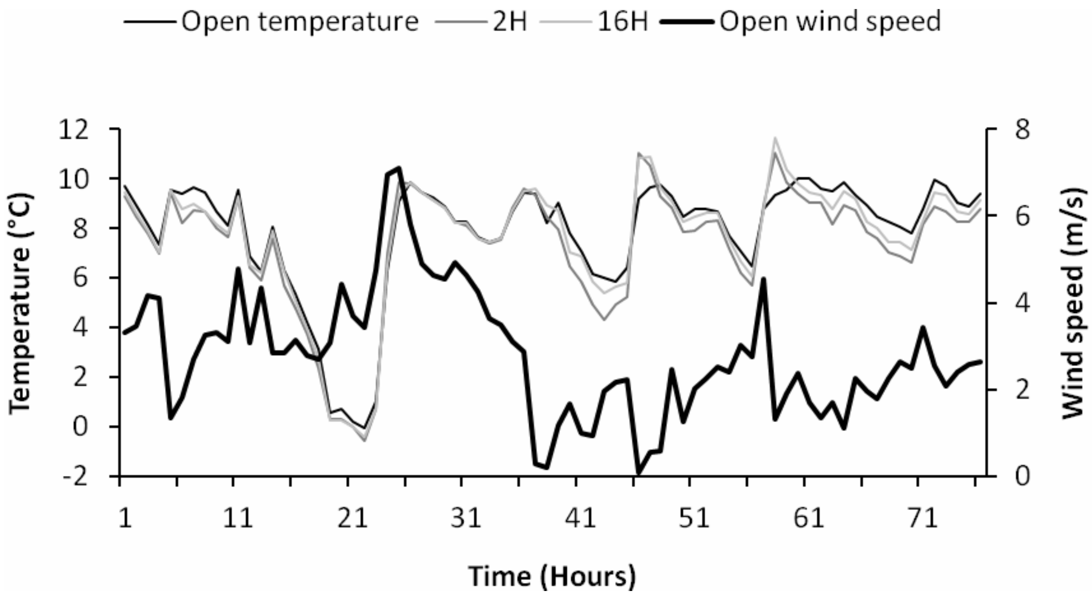

Figure 3-14. Temperatures at 2H and 16H on the south side of cadaghi windbreak WB1 at C&B Farms during cold fronts when the wind direction was between 0 and 180 degrees to the windbreak.

Relative Humidity (RH) Modification

Nighttime RH on the south side of the redcedar windbreak was realatively higher than in the open beginning in February and was similar at all locations (Figure A-10). Nighttime RH was similar at all locations at the same wind speeds (Figure 3-15). RHs at all locations were similar to open when the wind speed was less than 2.5 m/s. However, RHs all locations were higher than in the open when the wind speed was greater than 2.5 m/s and highest RH (4% higher than in the open) was recorded at 14H when the wind speed was 2.5-5 m/s.

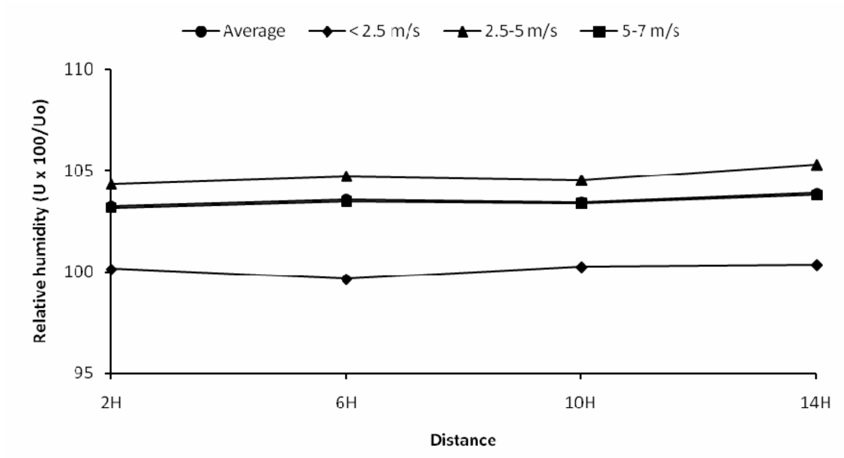

Figure 3-15. Nighttime relative humidity (RH) on the south side of eastern redcedar windbreak at SWFREC during different wind speeds. U is the RH south of the windbreak and Uo at the control station.

Daytime RH also showed the same pattern, except that RHs at 2H was slightly lower and at 10H and 14H was slightly higher than in the open till mid February (Figure A-11). From March, RHs at all locations were higher than in the open. On average RH at all locations were at least 9% higher than in the open (Figure 3-16). RH was lowest at 2H and highest at 14H. The difference in RH between 2H and 14H was at least 2.8%.

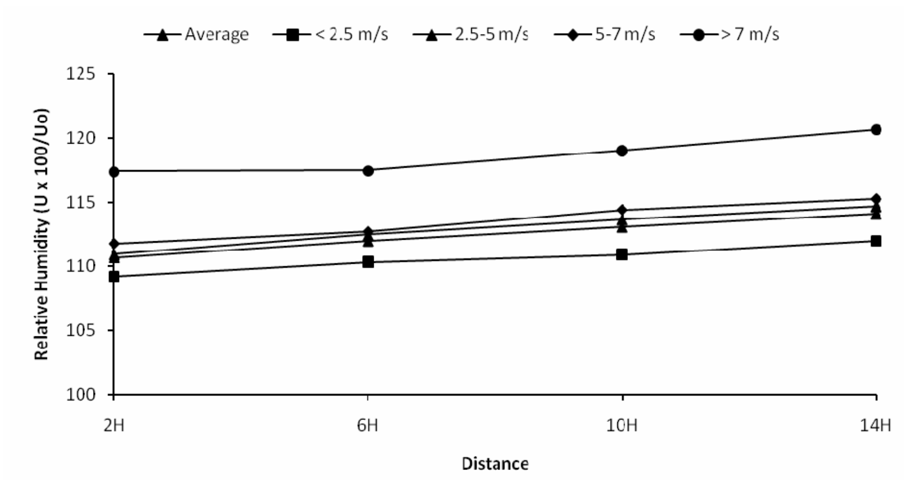

Figure 3-16. Daytime relative humidity (RH) on the south side of eastern redcedar windbreak at SWFREC. U is the RH south of the windbreak and Uo at the control station.

South of WB1 at C&B Farms, 6H had the highest (3.8%) nighttime RH, and 16H had the lowest among all locations until the end of May when the wind direction was from the north (Figures 3-17 and A-12). RHs at all measurement locations were higher than in the open except at 16H, which was approximately 1% lower. Compared to RH when wind speed was 5-7 m/s, RHs at all locations (except 16H) were higher than in the open when the wind speed was below 5 m/s. When the wind direction was from the south, similar observations were made at measurement locations north of WB2. The highest RH was recorded at 6H (from WB2) among all locations (not shown here).

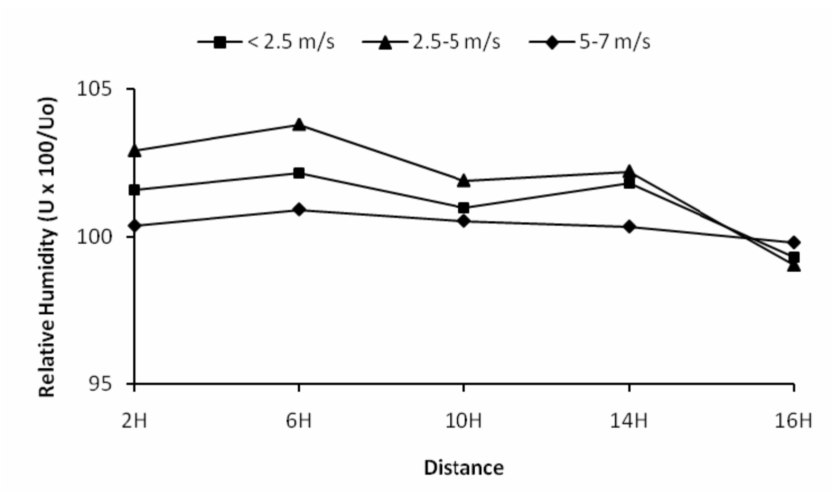

Figure 3-17. Nighttime relative humidity (RH) on the south side of cadaghi windbreak WB1 at C&B Farms when the wind direction was north. U is the RH south of the windbreak and Uo at the control station.

South of WB1, all locations except 16H generally had higher daytime RHs compared to the open when the wind direction was from the north (Figure A-13). On average, RHs at 14H was similar to open and other locations had slightly lower RH than in the open, with lowest at 16H (~ 2%, Figure 3-18). When the wind was from the south, measurement locations north of WB2 also showed the similar pattern. 2H and 31H had slightly lower but 6H had slight higher RH than in the open (not shown here).

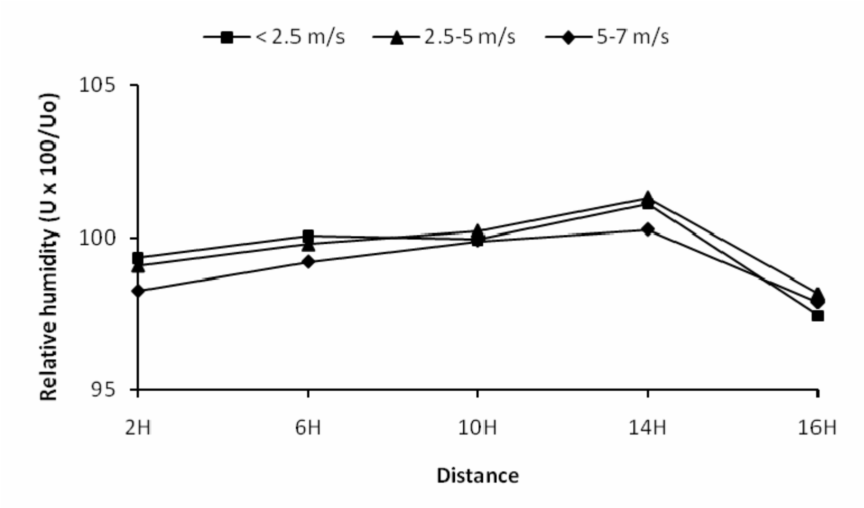

Figure 3-18. Daytime relative humidity (RH) on the south side of cadaghi windbreak WB1 at C&B Farms when the wind direction was from north. U is the RH on the leeside of the windbreak and Uo at the control station.

Discussion

Wind speeds on the leeside of the windbreaks were at least 22 and 20% lower than in the open at SWFREC and C&B Farms during normal weather conditions, respectively. Wind reduction varied with windbreak porosity, wind speed and wind direction. As expected, higher reductions were observed at locations closer to windbreaks when wind directions were perpendicular to the windbreak. Regardless of the wind direction, maximum wind reductions were recorded at 2H south of the redcedar windbreak, but at C&B Farms, maximum reduction was recorded at 2H only when the direction was less than 45 degrees and greater than 135 degrees to the windbreak, and at 4H or 6H when wind direction was between 45 and 135 degrees to the windbreak. This was primarily due to differences in windbreak porosities. Porosity of redcedar windbreak was uniform and comparatively lower than those of cadaghi windbreaks. Relatively porous cadaghi windbreaks allowed more winds to pass through them when the direction was perpendicular. The extent of wind reduction on the leeside also depended on open wind speed and wind direction. Maximum reductions were observed at lower open wind speeds regardless of wind direction. However, for the range of same wind speeds (e.g., > 5 m/s) more wind reductions were obtained on the leeside (all windbreaks) when the wind direction was between 45 and 135 degrees to the windbreak compared to when direction was less than 45 and greater than 135 degrees to the windbreak. Wind reductions on the leeside in this study varied between 0% and 100%, but were generally lower than in other studies. Wind speeds have been recorded between 40% and 100% on the leeside (Brenner et al., 1995; Zhang et al., 1995).

In Australia, wind reduction was generally related to windbreak porosity and wind on the leeside was equivalent to windbreak porosity (Cleugh et al., 2002). Windbreaks that had low but uniform porosity in this study were more effective in reducing wind and wind reduction was within the expected range, i.e., wind speed at 2H south of redcedar windbreak with 17.4% porosity was approximately 18% of the open wind speed (Figure A-1). Similarly, relative wind speeds closer to the windbreaks south of cadaghi WB1 and north of WB2 were also nearly equivalent to their porosities (Figures A-3 and A-4). Distance of wind reduction on the leeside depends on the windbreak height and can extend up to 30H (Cleugh and Hughes, 2002; Vigiak et al., 2003) and sometimes up to 60H (Caborn, 1957). Wind reduction on the leeside of the cadaghi windbreaks were observed up to 31H at C&B Farms. Wind reduction up to longer distances at C&B Farms was also partly due to the compound effects of two windbreaks planted parallel to each other.

Reduced wind speed on the leeside influnced temperature and relative humidity. At SWFREC, nighttime temperature was 1% lower compared to open temperature at 2 and 6H, and 1% higher at 10 and 14H. An opposite pattern was observed during the day, with relatively higher temperatures near the windbreak (up to ~ 3%). Similar results were observed at location south of WB1 and north of WB2 at C&B Farms. Temperature generally increased with the reduction in wind speed, and the location of maximum temperature coincided with the location of minimum wind speed (Cleugh et al., 2002). Temperature and RH patterns in the current study were consistent with observations made in other locations (McAneney et al., 1990; Cleugh, 1998). Maximum temperatures were recorded at locations closer to the windbreaks where wind reduction was the most. RH was generally higher on the leeside compared to open. Foereid et al. (2002) also observed increased temperature near a willow windbreak in Denmark during the day, but a decrease at night. RH also increased in the sheltered area during the day (Sudmeyer et al., 2002a). However, compared to wind reduction, temperature and RH modifications were insignificant and such modification extended up to 10-12H on the leeside of the windbreak (Cleugh et al., 2002). There was also an effect of season on microclimate modificaiton in the current study. Increase in temperature on the leeside gradually decreased after May, but RH generally increased on the leeside compared to open. Plant transpiration is a cooling process that increases humidity in the surrounding area. Increases in soil moisture lowered temperature and increased RH in the later part of the study.

Results of this study suggest that windbreaks of low porosity can lower winter temperatures near the windbreak on the leeside and make freeze events worse. Temperature inversion takes place at night and stratification of air layers occurs on the leeside of the windbreak. Reduced wind on the leeside of low porous windbreaks can cause less exchange of heat between air layers. During the process, cold air, which is heavier, settles near the ground. This can lead to formation of frost in the sheltered area during calm nights (Brandle et al., 2004). In January 2009, frost formed in areas closer to cadaghi windbreak (WB1) at night during cold front. Crops near the windbreak suffered more damage compared to crops away from the windbreak, but frost did not form in areas without windbreaks. Cold sensitive crops may suffer more damage during such events. Such catastrophic events could be avoided by allowing some air to flow through the windbreak as temperature on the leeside and open seem to be similar when wind speed was greater than 2 m/s (Figure 3-14).

One of the conditions required for citurs canker dispersal is wind-driven rain with speeds greater than 8 m/s. At this wind speed, bacteria are dispersed within trees and from tree to tree (Timmer et al., 2000), and wind speeds greater than 8 m/s are required to force canker bacteria through stomates and wounds (Graham et al., 2004). Wind scar in citrus occurs at wind speeds as low as 6.7 m s^{-1} (Metcalf, 1937). Results suggest that well designed single-row cadaghi windbreaks have the potential to reduce physical damage to crops by reducing wind speed and could potentially lower canker infection in citrus.

Conclusions

Winds on the leeside of the windbreaks were reduced and were generally lower than in the open when the direction was between 0 and 180 degrees to the windbreak. Maximum wind reductions were obtained on the leeside of low porous windbreaks. Distance and extent of wind reduction increased up to 31H between two windbreaks (WB1 and WB2) planted parallel to each other. Windbreaks also increased temperature up to 2.9° C and RH up to 20% on the leeside. However, temperature and RH modifications were relatively less compared to wind reduction. Temperature reduction near low porous windbreaks during cold fronts may be damaging to crops. By reducing wind speed, windbreaks can potentially restrict the movement of wind-borne pathogen such as citrus canker and lower infection by minimizing damage to plant parts.

CHAPTER 4
ROOT DISTRIBUTION IN FAST-GROWING CADAGHI (*Corymbia torelliana*) TREES IN WINDBREAKS IN FLORIDA

Introduction

Live windbreaks are planted primarily to reduce wind speed, thus reducing soil erosion, modifying microclimate and enhancing crop production. Although overall crop yield increases on the leeside of the windbreaks, lower yields can be expected adjacent to windbreaks due to above- and belowground competition. Compared to aboveground competition for light, much of the competition was belowground for soil resources such as nutrients and moisture (Caldwell, 1987). Competition for resources is usually most intense closest to the windbreak and decreases with the distance.

Belowground competition was a function of root density and root distribution (Clarkson, 1985). Effective management of this competition was best obtained by root pruning along the windbreak-crop interface (Rasmussen and Shapiro, 1990; Hocking and Islam, 1998). This is especially important when both the windbreak species and target crop grow roots in the same soil horizons and compete for nutrients. Though most tree species produce relatively more roots in the surface soil compared to deeper soil (Dawson et al., 2001; Laclau et al., 2001; Odhiambo et al., 2001; Sudmeyer et al., 2004; Falkiner et al., 2006), others such as cherry (*Prunus avium*) developed deeper roots when there was competition at the surface (Dawson et al., 2001).

Though vegetable growers in Florida mostly use ryegrass (*Lolium perenne*) (Workman et al., 2003) and sugarcane (*Saccharum* spp.) as windbreaks, Florida citrus industry is adopting tree windbreaks to manage citrus canker (*Xanthomonas campestris* pv. *citri*). After citrus canker was widely spread during the 2004/05 hurricane seasons, the disease has increasingly become devastating to the citrus industry in Florida. The disease is spread by windblown rains (Gottwald et. al., 1992; Graham and Gottwald, 1992) and damaged plant parts increase infection. Thus, there has been increased interest in using windbreaks to slow canker spread and lower infection. Because of the rapid spread of this disease, fast-growing tree species are widely preferred for windbreaks, and non-natives such as eucalypts (*Eucalyptus* spp.) and cadaghi (*Corymbia torelliana*) are becoming common in Florida farm windbreaks (Rockwood et al., 2008).

Unfortunately, fast-growing species generally have a higher rate of root extension and production than slow-growing species. Therefore, the potential for belowground competition with the crops is high. For example, horizontal root extension in *E. camaldulensis*, a fast-growing species, exceeded 2.5 m $year^{-1}$ while the rate was approximately half in teak (*Tectona grandis*) and jackfruit (*Artocarpus heterophyllus*) (Calder et al., 1997). Fast-growing cottonwood also produced relatively higher (1.4 cm cm^{-3}) root length density (root length per unit volume of soil, L_V) compared to American sycamore (*Platanus occidentalis*) and loblolly pine (*Pinus taeda*), in which L_V was 1.0 and 0.2 cm cm^{-3}, respectively (Coleman, 2007). Root management therefore is essential to maintain high levels of production closer to windbreaks of fast-growing species.

Root management, however, is costly because of complex and variable root architecture, non-uniform distribution of roots and the opaque quality of soil (Bengough et al., 2000). Root management is also made difficult by the variable root growth characteristics of different species and root distribution with depth, soil type, the composition of soil profiles (Sudmeyer, 2002; Sudmeyer et al, 2004) and soil environment (Comeau and Kimmins, 1989; Hamblin et al., 1990; Nepstad et al., 1994; Knight, 1999; Moroni et al., 2003).

Information such as lateral extent of root growth, number and length of roots in different size classes and distribution with depth, which are important for underground competition management, are lacking for cadaghi. Because nutrient uptake by plants depends highly on the value of L_V, it is a widely measured root variable (Nye and Tinker, 1969; Barber and Silberbush, 1984). L_V is influenced by plant species (Jones et al., 1998; Knight, 1999; Sudmeyer, 2002; Sudmeyer et al., 2004), root size (Moroni et al., 2003) and root density. Measuring L_V is time consuming and takes about five times the time required to measure root number (N) (Vespraskas and Hoyt, 1988). N is a good predictor of root length in some species (Crocker et al., 2003). When roots are randomly distributed in three dimensions (isotropic) in a small volume of soil, L_V and N are related by L_V=2N (Kendall and Moran, 1963; Melhuish and Lang, 1968). When roots are anisotropic, the average number of roots in three-dimensions (X, Y and Z, N_{AVG}) can be used to test the relationship (Baldwin et al., 1971; Marriott, 1972). The relationship has been tested in several different species, but success has been limited (Bennie et al., 1977; Drew and Saker, 1980; Bland, 1989; Escamilla et al., 1991; Lopez-Zamora et al., 2002; Adegbidi et al., 2004). If this relationship can be established in cadaghi, L_V can be estimated from N, which can significantly minimize time and cost for cadaghi root management.

This study was conducted at C&B Farms in south Florida where cadaghi trees were planted in windbreaks. The objectives were to 1) examine root distribution and 2) test L_V=2N relationship in cadaghi trees. The hypothesis was that the older trees produce more roots and N is a good predictor of L_V.

Materials and Methods

Study Area

The study was conducted at C&B Farms (26°27'30"N, 80°58'46"W) near Clewiston, Florida, where different vegetables are grown throughout the year. Primary irrigation channels divide the farm into blocks. The farm employs seepage irrigation, and secondary irrigation channels supply water to crop fields from the primary channels. Single-row cadaghi windbreaks are planted along primary irrigation channels (Figure 4-1), with ~1.5 m between the windbreaks and the channels. Some windbreaks are established and functional while others are in the early stages of development. To drain surface water runoff from crop fields efficiently during the rainy season, a gentle slope is maintained from the north to the south, so that the north end of the field is ~50 cm higher than the south end.

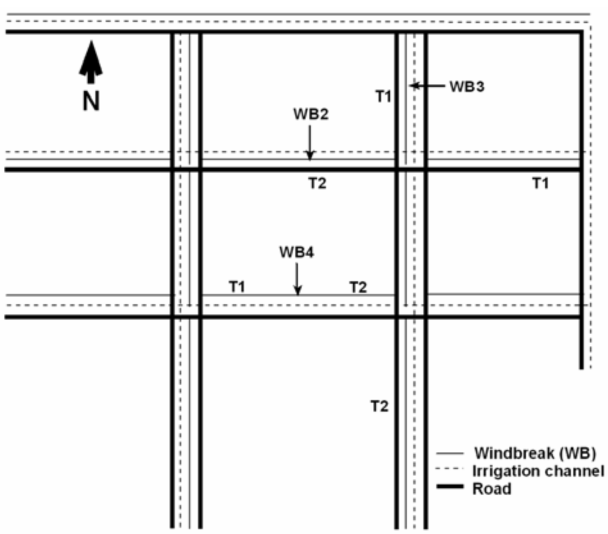

Figure 4-1. Part of C&B Farms showing relative position of three cadaghi windbreaks (WB) and the approximate location of trenches (T) used for root study.

Methods

Three established windbreaks (WB) were studied (Table 4-1, Figure 4-1). WB2 is east-west oriented, and WB4 is ~300 m south of WB2. WB3, the easternmost windbreak, is oriented north-south. Both WB2 and WB3 have an access road (~5 m wide) on one side and an irrigation channel (~3-3.5 m wide) on the other side at ~1.5 m from the windbreak. WB4 is at the end of the crop field and has an irrigation channel on the south of the windbreak and a crop field on the north. WB2 and WB4 are both 8-years old.

Table 4-1. Number of trees (n), age (years), height (m), diameter at breast height (DBH, cm) and spacing between trees (m) of three cadaghi windbreaks at C&B Farms used for root study (mean value ± standard error).

Windbreak	Age	Height	DBH	Spacing
WB2 (n=51)	8	11.1 ± 0.2	26.7 ± 0.8	4.9 ± 0.1
WB3 (n=72)	6	8.8 ± 0.2	19.9 ± 0.5	3.3 ± 0.1
WB4 (n=37)	8	10.0 ± 0.2	24.9 ± 0.7	4.5 ± 0.2

Measured in September 2008 before root sampling.

Five windbreak sections (~45 m long) in each of WB2 and WB3 were randomly selected (see chapter 3). In shorter (length) windbreak WB4, only four windbreak sections (~45 m long) were randomly selected. Each tree in a windbreak section was measured in September 2008 for total height and diameter at breast height (DBH) (Table 4-1). Distance between trees in all windbreaks was also measured. Two trees of average height and DBH were randomly selected in each windbreak. Using a backhoe, trenches (T, Figure 4-1) 2 m long x 1 m wide x 1 m deep) were dug at 2 and 4 m from each tree (on the same side of the tree parallel to the windbreaks) in October/November 2008 for root sampling. The trench face was smoothed using a shovel. A 1 x 1 m area was selected on a trench face perpendicular to the tree for root measurement. Each 1 x 1 m area was divided into 10 x 10 cm grids, and the number of roots (N) in each grid was counted. Roots were classified by diameter into fine roots (<1 mm), medium roots (1–5 mm) and coarse roots (5–20 mm) (Coleman, 2007). Since four of the trenches were beside the access road and there was concern about the impact of soil compaction on root distribution, soil bulk density was also measured for each depth class. A soil sample for bulk density estimation was collected by driving a metal container of known volume into the trench wall in each depth class. Only one sample per depth was collected from each trench.

Three grids representing the range of number of root counts were selected from each depth (Lopez-Zamora et al., 2002), and 1,000 cm^3 soil samples were removed from each selected grid to estimate L_V using a 10 x 10 x 10 cm metal container. Soil cubes were removed only from the depths with roots, leading to varying sample numbers for L_V and root weight in different windbreaks. Roots present at the other two faces of the cube (N_Y and N_Z, where Y is the vertical face perpendicular to X and Z the basal horizontal face) were counted and their diameters measured. Roots were counted only from the front, left and bottom side of X, Y, and Z cube faces, respectively. Soil samples were transported to the lab, roots were washed, and their total length was estimated using Tennant's (1975) intercept counting technique. Root samples were then oven dried at 55° C for a month until constant weights were obtained to determine dry root weight. Root weight was expressed as grams of root per 1000 cm^3 of soil.

Statistical Analysis

Cadaghi roots were present in all trenches at a distance of 2 m from the windbreak. In trenches at 4 m from the windbreak, roots were present only in WB3. Therefore, only the trenches at 2 m from the windbreaks were used in the analysis. Because roots were present only up to 50 cm deep in all six trenches, depths below 50 cm was not included in the analysis. N, L_V and root weight means were calculated for windbreak, depth and root sizes. Though WB2 and WB4 were the same age, they were considered as a factor in the model to examine root distribution under different land uses and soil environments. All analyses were done in SAS 9.2 (SAS Institute Inc., 2008).

All root variables were assumed spatially correlated. Both PROC MIXED (for continuous response variables) and GLIMMIX (for categorical or continuous response variables) provide options to take into account correlation in dependent data. The PROC MIXED procedure was used to test the differences in bulk density at 2 m from three windbreaks treating windbreak (WB) and depth as fixed effects and trench as a random effect. The interaction was not significant and excluded from the model. The model was

$$Y_{ijk} = \mu + \alpha_i + \beta_j + c_{ik} + e_{ijk} \qquad (4\text{-}1)$$

where Y_{ijk} is bulk density in windbreak i, depth j, trench k; μ is the overall mean; α_i, β_j and c_{ik} are the effects due to windbreak i, depth j and trench k within windbreak i, respectively; and e_{ijk} the error.

For testing differences in average root number exiting the trench face (N_X) at 2 m in three windbreak trees, a generalized linear model was initially considered assuming Poisson data distribution (using the PROC GLIMMIX procedure). Windbreak (WB), depth and bulk density were considered the fixed effects and trench a random effect. However, since root counts in sixty percent of the 10 x 10 cm grids were zero-valued, there was significant over-dispersion detected in this model. Therefore, zero-inflated Poisson (ZIP) regression and Hurdle models in PROC NLMIXED were estimated with the same effects. Both ZIP and Hurdle models are mixture models that are widely used to model response data with excess zeros. In the ZIP model, a proportion, π, of the responses are zero, and the remainder follow a Poisson distribution with average number of roots, λ. A logit or probit function is used to model the inflation probability, π and a log function is used to model the mean function, λ (Ridout et al. 1998; Liu and Cela, 2008).

The final ZIP model included three covariates in the logit function for π, and a covariate in the mean function for λ.

$$\mathrm{logit}(\pi_i) = p_0 + p_1 WB + p_2 Depth + p_3 BD \qquad (4\text{-}2)$$

$$\lambda_i = \log(\mu_i) = q_0 + q_1 WB \qquad (4\text{-}3)$$

where WB, depth and BD are the effects of windbreak, depth and bulk density, respectively; p_0, p_1, p_2, p_3, q_0, and q_1 are parameters to be estimated.

The probability density function of a ZIP model is given by

$$P(Y = y) = \begin{cases} \pi + (1-\pi)\, e^{-\lambda}, \; y = 0 \\ (1-\pi)\dfrac{\lambda^y e^{-\lambda}}{y!}, \; y > 0 \end{cases} \qquad (4\text{-}4)$$

In a Hurdle model, the probability of excess zeroes, π, is estimated using the actual proportion of zeroes in the data, and a truncated Poisson or Negative binomial distribution is used to model positive outcomes (Ridout et al., 1998; Liu and Cela, 2008). As in the ZIP model, a log function is used to model λ.

The final Hurdle model included three covariates in the logit function for π, and a covariate in the mean function for λ.

$$\mathrm{logit}(\pi_i) = m_0 + m_1 WB + m_2 Depth + m_3 BD \qquad (4\text{-}5)$$

$\lambda_i = \log(\mu_i) = n_0 + n_1 WB$ (4-6)

where WB, Depth and BD are the effects of windbreak, depth and bulk density, respectively; m_0, m_1, m_2, m_3, n_0, and n_1 are parameters to be estimated.

The probability density function of a Hurdle model is given by

$$P(Y = y) = \begin{cases} \pi, \ y = 0 \\ (1-\pi)\dfrac{\lambda^y e^{-\lambda}}{y!(1-e^{-\lambda})}, \ y > 0 \end{cases} \quad (4\text{-}7)$$

Since WB is a categorical variable, dummy variables were used to define WB2 and WB3 with WB4 as the base (intercept only) in the NLMIXED procedure.

To estimate cadaghi root growth direction preference (isotropy), the PROC GLIMMIX procedure (root number being a count data) was used to compare differences in average root numbers in the three faces of the 10 x 10 x 10 cm soil cubes. Separate tests were first performed on data sets from individual windbreak trees. Data from all three windbreak trees were then combined and the test was performed on the combined data set. Interaction terms were not significant and therefore were not included in the model. The model for individual and combined data sets was

$Y_{ijkl} = \mu + \alpha_i + \beta_j + c_k + e_{ijkl}$ (4-8)

where Y_{ijkl} is the number of roots exiting the faces of the soil cube l in direction i, depth j and trench k; μ is the overall mean; α_i, β_j, and c_k are the effects due to direction i, depth j, trench k, respectively; and e_{ijkl} the error.

The PROC MIXED procedure was used to analyze L_V treating windbreak (WB) and depth as fixed effects and trench as a random effect using model 4-9.

$Y_{ijkl} = \mu + \alpha_i + \beta_j + c_{ik} + (\alpha\beta)_{ij} + e_{ijkl}$ (4-9) where Y_{ijkl} is the L_V in cube l in windbreak i, depth j and trench k within windbreak i; μ is the overall mean; α_i, β_j, c_{ik} and $(\alpha\beta)_{ij}$ are the effects due to windbreak i, depth j, trench k within windbreak i and the interaction between windbreak and depth, respectively; and e_{ijkl} the error.

Number of roots exiting the three faces of the soil cube were averaged by depth to get N_{AVG}. Data from all three windbreak trees were combined and the PROC MIXED procedure was used to test $L_V=2N_X$ and $L_V=2N_{AVG}$ relationship. Interaction was not significant and was excluded from the model. The final model was

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + c_k + e_{ijkl} \qquad (4\text{-}10)$$

where Y_{ijkl} was the L_V in soil cube l with N_X or N_{AVG} i, depth j, trench k; μ is the overall mean; α_i, β_j and c_k are the effects due to N_X or N_{AVG} i, depth j and trench k, respectively; and e_{ijkl} the error.

The PROC MIXED procedure was used to analyze root dry weight treating windbreak (WB) and depth as fixed effects and trench as a random effect using model 4-11. The distribution of root dry weight was significantly non-normal and was log transformed. Interaction was also considered in the model but was not significant.

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + c_{ik} + e_{ijkl} \qquad (4\text{-}11)$$

where Y_{ijkl} is the log of root dry weight in cube l in windbreak i, depth j and trench k within windbreak i; μ is the overall mean; α_i, β_j and c_{ik} are the effects due to windbreak i, depth j and trench k within windbreak i, respectively; and e_{ijkl} the error.

Results

Soil Description

The soil in the area was poorly drained Myakka sand (Sandy, siliceous, hyperthermic Aeric Haplaquods). Only the top soil layer was disturbed, and the soil profile below 20 cm depth was still natural. The top soil was dark grey in color, and hardpans were present between 20-30, 30-40 and 20-30 cm depths in WB2, WB3 and WB4, respectively. White sand was generally present between 40-60 cm, and reddish brown sand was present below 60 cm. Soil bulk density at 2 m from the windbreak was highest in WB2 (Figure 4-2).

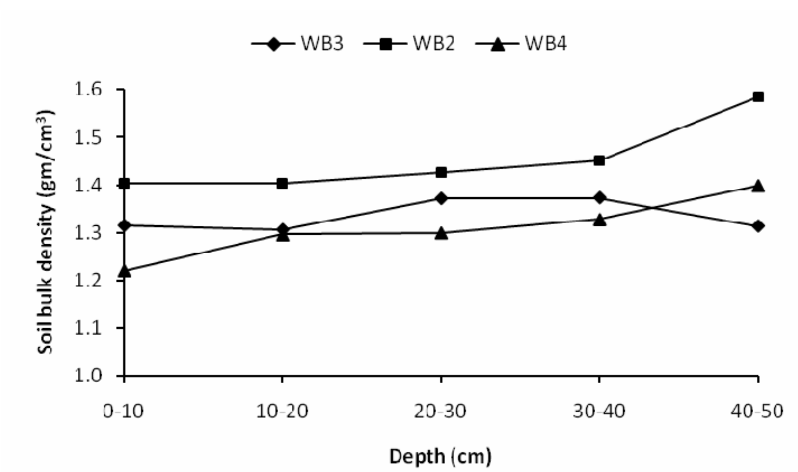

Figure 4-2. Soil bulk density at different depths at 2 m from the three windbreaks at C&B Farms.

The effect of windbreak location (WB) on bulk density was significant only at a 10% level (Table 4-2); mean soil bulk density was significantly different between WB2 and WB4 (Table 4-3).

Table 4-2. Type 3 test of fixed effects for bulk density in three windbreaks at C&B Farms.

Effect	Num DF	Den DF	F-value	P-value
WB	2	5.9	3.70	0.0912
Depth	4	11.4	1.25	0.3441

Table 4-3. Difference of bulk density least squares means between three cadaghi windbreaks at C&B Farms.

Difference	Estimate	SE	P-value
WB2 vs. WB3	-0.10	0.05	0.1092
WB2 vs. WB4	0.14	0.05	0.0393
WB3 vs. WB4	0.04	0.05	0.4800

Vertical Root Distribution

The numbers of roots on the trench face were highly variable, and root distribution did not show any consistent pattern (Figure 4-3). Roots were present on the trench face at 4 m from the windbreak only in WB3. Roots extended beyond 3 m in WB2, but did not exit on the trench face at 4 m from the tree. All roots on the trench face at 2 m from the windbreaks were smaller than 20 mm in diameter and were restricted to the top 50 cm of soil (Figure 4-3).

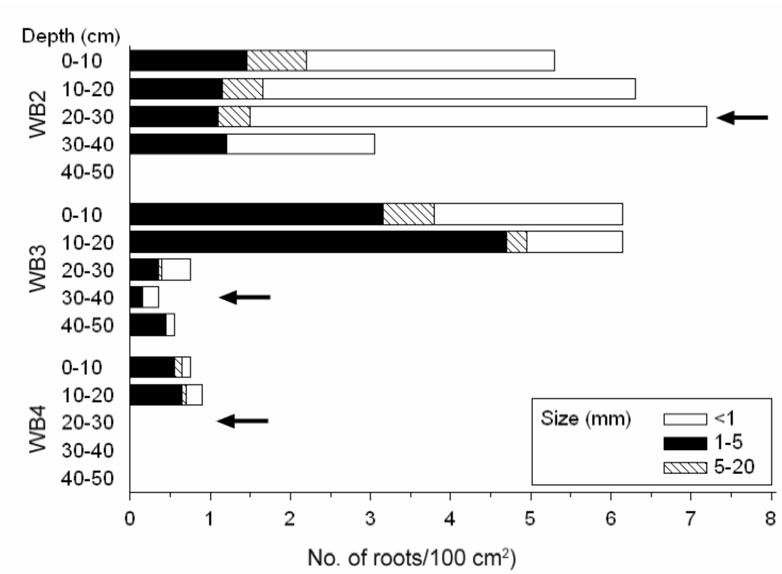

Figure 4-3. Vertical root distribution at 2 m from three cadaghi windbreaks at C&B Farms by root size and windbreak (Arrow indicates the position of hardpan).

Average numbers of roots in WB2, WB3 and WB4 trees were 4.3, 2.7 and 0.3 roots per 100 cm^2, respectively. Approximately 88.2% of the roots were present in the upper 20 cm of soil in WB3, and 53.1% were present in the upper 20 cm of soil in WB2;

however, all roots were restricted to the upper 20 cm in WB4 trees. WB3 and WB4 trees had relatively more medium roots (63.1% and 72.7%, respectively). Fine roots constituted 70% of the roots in WB2 trees. Coarse roots were the least prevalent in all three windbreak trees and were present only up to 20-30 cm in WB2 and WB3, and up to 10-20 cm in WB4 trees. Only WB2 and WB3 tree fine and medium roots were able to penetrate the hardpan.

Among the three models (generalized linear model using the PROC GLIMMIX procedure, ZIP model and Hurdle) that were used to estimate root number, the ZIP model was considered the best following various statistical criterion. The values of the Akaike's Information criteria (AIC) and the small-sample bias corrected version of the AIC (AICC) were the smallest for the ZIP model (Table 4-4). Therefore, the results are presented only for the ZIP model.

Table 4-4. Fit statistics (AIC, AICC), inflation probability (pi) and mean (Lambda) from generalized linear model (using the PROC GLIMMIX procedure), zero-inflated Poisson (ZIP) and Hurdle models for predicting root number.

Model	AIC	AICC	pi	Lambda
Poisson	1534.5	1534.7	-	1.1
ZIP	1108.5	1109.0	0.59	5.2
Hurdle	1108.8	1109.3	0.60	5.2

Mean root counts in WB2 and WB3 trees were significantly higher than in WB4 trees given that roots were present (Table 4-5). Depth significantly increased and bulk density decreased zero-inflation probability. Both WB2 and WB3 trees significantly decreased zero-inflation probability compared to WB4 trees.

At 4 m from the windbreak, roots were present only in WB3 trees and confined to the top 40 cm of soil (Figure 4-4). The average number of roots was 2.0 per 100 cm^2. There were relatively more coarse roots at depths 0-10 and 10-20 cm (approximately

68% and 69%, respectively). Fine roots dominated depths 20-30 (73%) and 30-40 cm (85%). Of the total roots at 4 m, 61.2% were coarse roots.

Table 4-5. Mean, standard error (SE), P-value, and lower and upper bounds for the 95% confidence limits for model coefficients from the zero-inflated Poisson (ZIP) model for root numbers (roots per 100 cm^2) exiting the frontal face of the trench walls. WB4 was set to zero to define dummy variable.

Coefficient	Mean	SE	P-value	Lower bound	Upper bound
			Inflation probability function		
Intercept	4.3	1.90	0.0254	0.53	8.01
WB					
WB2	-2.75	0.55	<.0001	-3.83	-1.68
WB3	-2.76	0.50	<.0001	-3.75	-1.77
Depth	1.39	0.17	<.0001	1.05	1.73
Bulk density	-4.33	1.56	0.0060	-7.40	-1.25
			Mean function		
Intercept	0.91	0.20	<.0001	0.51	1.31
WB2	1.15	0.21	<.0001	0.73	1.56
WB3	0.77	0.21	0.0003	0.35	1.19

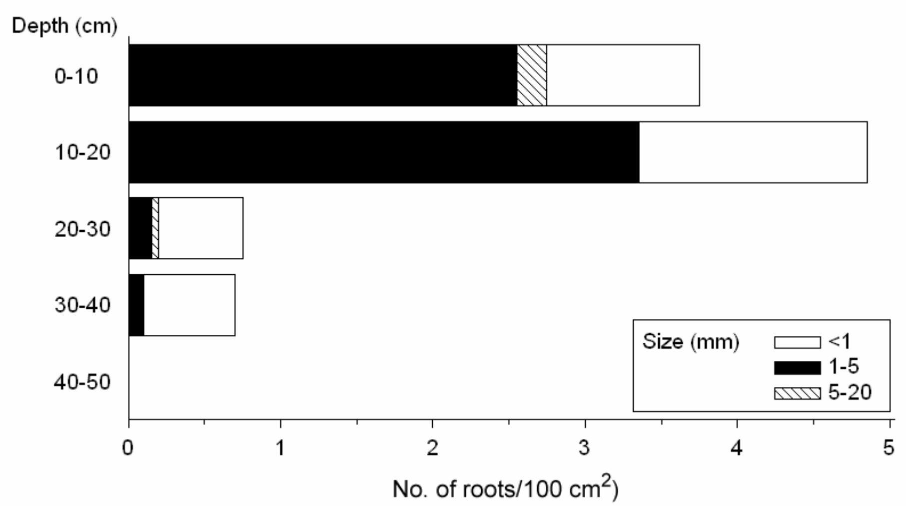

Figure 4-4. Vertical root distribution at 4 m from the cadaghi windbreak WB3 at C&B Farms.

Root Isotropy

Root distributions at 2 m from the windbreaks were anisotropic (Table 4-6). The frontal face of the trench wall (X) had the highest numbers of roots. In all three windbreaks individually and from all windbreaks combined, average root numbers were ranked $N_X > N_Y > N_Z$.

Table 4-6. Number of samples (n) and mean root number per 100 cm^2 (N) for the three faces of 10 x 10 x 10 cm soil cubes at 2 m from three cadaghi windbreaks (WB) at C&B Farms individually and samples from all windbreaks combined.

WB	Face	n	N (roots/100 cm^2)
WB2	X	18	7.3
	Y	18	3.8
	Z	18	0.9
WB3	X	24	5.5
	Y	24	2.3
	Z	24	0.4
WB4	X	6	2.8
	Y	6	1.8
	Z	6	0.5
All samples	X	48	5.8
	Y	48	2.8
	Z	48	0.6

A generalized linear mixed model was used to determine the effect of direction of root growth and depth on root number. Direction of root growth had a significant effect on root number in all three windbreak trees individually (Table 4-7). It was also significant when tested using combined data from all three windbreak trees (Table 4-7).

Table 4-7. Type 3 test of fixed effects for root number (N) in windbreaks WB2, WB3, WB4 and data from all three windbreaks combined (all samples) at C&B Farms.

Effect	Num DF	Den DF	F-value	P-value
WB2				
Direction	2	39.1	15.69	<.0001
Depth	3	31.2	4.49	0.0099
WB3				
Direction	2	56.2	21.76	<.0001
Depth	4	56.8	4.59	0.0028
WB4				
Direction	2	14	3.51	0.0582
Depth	1	14	0.26	0.6198
All samples				
Direction	2	137	35.90	<.0001
Depth	4	137	0.34	0.8495

Least square means of root number in three faces of the cube (direction) were compared. Number of roots exiting all faces were significantly different in WB2 and WB3 trees (Table 4-8). In WB4 trees, only the roots exiting faces X and Z were significantly different. When the data from all three windbreaks were combined (all samples), roots exiting all three faces were significantly different.

Table 4-8. Difference of least squares means estimates, standard error (SE) and P-values for comparisons of root numbers exiting three faces of 10 x 10 x 10 cm soil cubes at 2 m from three cadaghi windbreaks at C&B Farms.

WB	Face comparison	Estimate	SE	P-value
WB2	X vs. Y	0.63	0.24	0.0115 [a]
	X vs. Z	2.10	0.39	< 0.0001[a]
	Y vs. Z	1.47	0.40	0.0008[a]
WB3	X vs. Y	0.86	0.25	0.0011 [a]
	X vs. Z	2.55	0.40	< 0.0001[a]
	Y vs. Z	1.68	0.42	0.0002[a]
WB4	X vs. Y	0.44	0.41	0.3066
	X vs. Z	1.73	0.66	0.0205[a]
	Y vs. Z	1.30	0.69	0.0809
All samples	X vs. Y	0.74	0.20	0.0003[a]
	X vs. Z	2.28	0.28	< 0.0001[a]
	Y vs. Z	1.52	0.29	< 0.0001[a]

[a] Means significantly different at a P-value of 0.05.

Root Length Density (L_V)

Average L_V was 314.9, 256.6 and 245.2 cm per 1000 cm^3 of soil for WB2, WB3 and WB4 trees, respectively (Figure 4-5). There was no significant effect of windbreak or depth on L_V, but the interaction was significant (Table 4-9).

Table 4-9. Type 3 test of fixed effects for root length density (L_V) in three windbreaks at C&B Farms.

Effect	Num DF	Den DF	F-value	P-value
WB	2	1.8	0.34	0.7495
Depth	4	35.9	1.21	0.3238
WB*Depth	4	35.6	3.17	0.0252

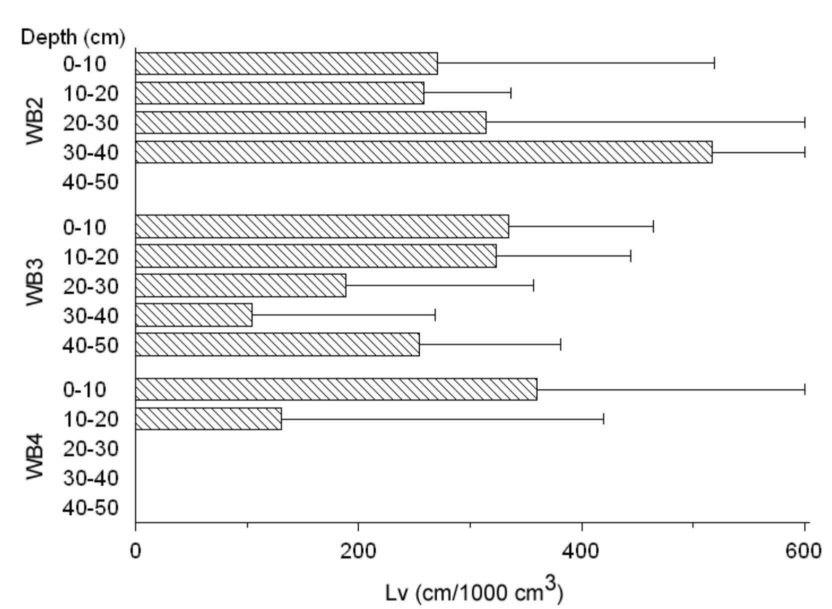

Figure 4-5. Root length density (L_V) means and standard errors for five soil depths at 2 m from three cadaghi windbreaks at C&B Farms.

The average L_V of trees at 4 m from windbreak WB3 was 187.2 cm per 1000 cm^3 of soil. The highest L_V (40.2%) was at 10-20 cm (Figure 4-6). L_V at other depths was similar.

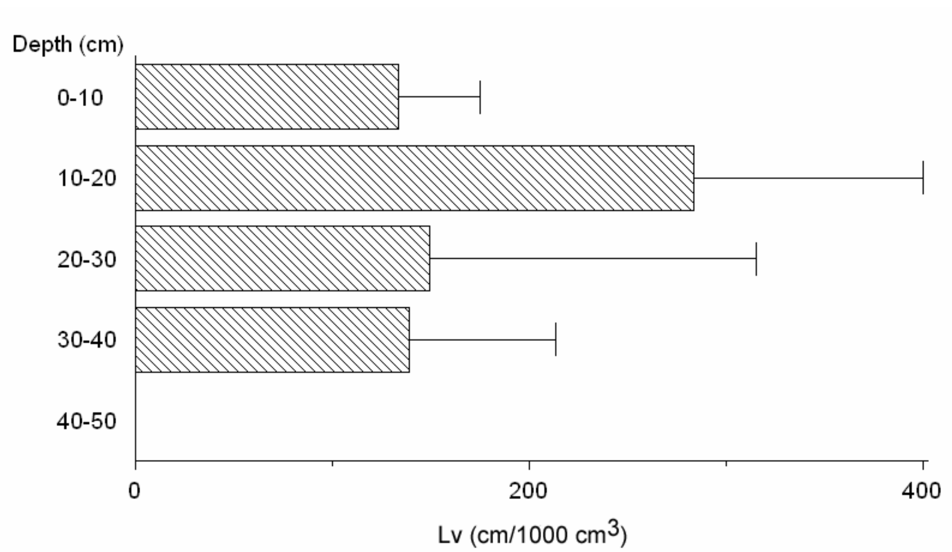

Figure 4-6. Root length density (L_V) means and standard errors for five soil depths at 4 m from cadaghi windbreak WB3 at C&B Farms.

Relation between L_V and N

Both N_X (p = 0.0046) and N_{AVG} (p = 0.0022) were significant variables for determining L_V in cadaghi trees. The coefficient of N_X was significantly different from 2 as its 95% confidence interval did not include 2. However, the coefficient of N_{AVG} was not significantly different from 2 (Table 4-10).

Table 4-10. Coefficients of number of roots exiting the frontal face (N_X) and average number of roots (N_{AVG}) exiting the three faces (X, Y and Z) of 10 x 10 x 10 cm soil cube combined over three cadaghi windbreaks at C&B Farms, their standard errors (SE), P-values and 95% confidence intervals.

Roots	Coefficients	SE	P-value	Lower	Upper
N_X	1.13	0.38	0.0046	0.37	1.89
N_{AVG}	3.07[a]	0.95	0.0022	1.16	4.97

[a]Not significantly different from 2 at a P-value of 0.05

Root Weight

Average root weights at 2 m from the windbreaks were 3.3, 3.4 and 1.3 g root per 1000 cm^3 of soil for WB2, WB3 and WB4 trees, respectively (Figure 4-7). The majority of root weight (more than 79%) was in the top 20 cm of soil in WB3 and WB4 trees, while WB2 trees had most of the root weight (63.6%) between 20-40 cm. There was no significant effect of windbreak and depth on log of root weight (Table 4-11).

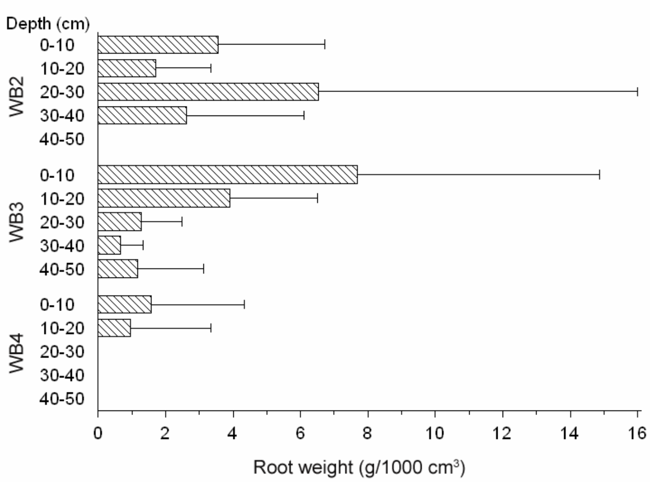

Figure 4-7. Root weight means and standard errors at 2 m from the windbreak for five soil depths in three cadaghi windbreaks at C&B Farms.

Table 4-11. Type 3 test of fixed effects for log of root weight in three windbreak trees at C&B Farms.

Effect	Num DF	Den DF	F-value	P-value
WB	2	2.3	1.66	0.3573
Depth	4	40.1	1.88	0.1323

At 4 m from the windbreak, the average root weight was 1.2 g root per 1000 cm^3 of soil in WB3 trees (Figure 4-8). Compared to other depths, the 10-20 cm depth had higher root weight.

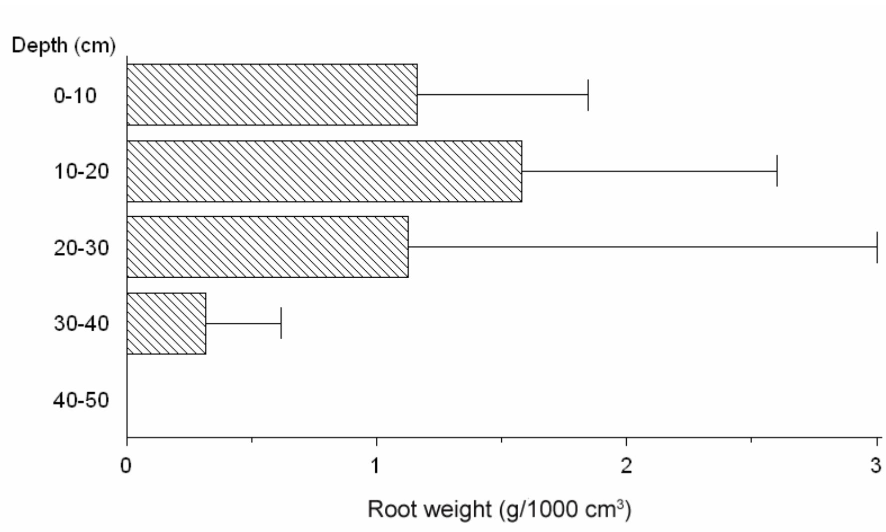

Figure 4-8. Root weight means and standard errors at 4 m from windbreak WB3 at C&B Farms.

Discussion

Numbers of roots in the windbreak trees were variable and did not show any distinct distribution pattern with depth. Roots were found only in the top 50 cm of soil. Larger diameter roots were limited in the upper soil layers and only fine and medium roots were able to penetrate the hardpan. Relatively more roots were observed in the surface soil in some studies, with an exponential decrease with depth in some cases (Dawson et al., 2001; Laclau et al., 2001; Odhiambo et al., 2001; Sudmeyer et al., 2004; Falkiner et al., 2006).

Species characteristics and soil factors such as soil type, compaction and nutrients regulated root growth and distribution in plants (Smit et al., 2000a; Lehmann, 2003). In Australia, dense soil layers were barriers to root growth. Root density decreased gradually in the upper sandy horizon, but the decrease was abrupt in clayey subsoils. In some species, roots were concentrated above the clayey subsoil (Sudmeyer et al., 2004). Water and nutrient availability also impacted root density (Fabião et al., 1995; Pronk et al., 2002; Ruiz-Sanchez et al., 2005), root production (Coleman, 2007) and root distribution (Neilsen et al., 2000; Sokalska et al., 2009). Apple (*Malus domestica*) trees developed shallow root systems when water was readily available at the surface, but in the absence of surface water, deep roots developed (Sokalska et al., 2009). Maritime pine (*P. pinaster*) also produced deep roots to access water in drier sites (Achat et al., 2008). However, cherry trees developed roots in surface soil because of the lack of competition (Dawson et al., 2001). It is likely that the hardpan, easy access to water (and potentially nutrients), and lack of competition limited root development only to the upper 50 cm of the soil.

As expected, average root number was significantly higher in the older windbreak (WB2) trees, except in WB4. Also, the number of roots in WB2 and WB3 were higher than in WB4 trees. Several factors influenced root density in WB4 trees. First, because of the gentle slope in the fields, the south end where WB4 is planted is ~50 cm lower than the north end. Water level in the primary irrigation channels at the south end is raised almost to ground level to force water in the secondary channels during cropping season from August/September to April/May. Roots generally did not grow in soils that had either seasonally (Morris and Campbell, 1991) or permanent high water table and grew up to the depth of soil above the water table (Begg et al., 1997; Falkiner et al., 2006). The presence of roots up to 40 cm in WB2, 50 cm deep in WB3 and 20 cm in WB4 trees generally corresponded to the normal water table around the windbreaks for most part of the year. Lack of aeration in the rooting zone potentially hindered root development and growth. Second, at the beginning of the cropping season (June-August), fields are disked almost up to the tree line at the south end of the field. The disks can easily penetrate 15-20 cm into the soil and can prune tree roots. As fields are disked every year, trees have to produce new roots. Almost all roots in WB4 trees were <5 mm in diameter.

Despite its young age, the presence of roots at 4 m in WB3 trees was surprising. Roots extended beyond 3 m in WB2 trees, but did not exit at 4 m. The road next to WB2 is used extensively while the one next to WB3 is used less frequently. Soil bulk density (both at 2 m and 4 m) in WB2 was higher than in WB3 and WB4 at all depths. Also the water in the secondary irrigation channel that runs parallel to WB3 at ~6 m from the windbreak fluctuates regularly. It is likely that the combination of less compact soil and fluctuating water (Nepstad et al., 1994) resulted in WB3 trees developing extensive root systems.

Cadaghi roots were anisotropic and N_X values were relatively high compared to N_Y and N_Z. However, the number of roots in species such as corn (*Zea mays*) (Chopart and Siband, 1999) and peach palm (*Bactris gasipaes*) were identical in all three directions (X, Y and Z) of the soil cube. If roots are measured correctly and the theory is applied to correct field conditions, the coefficient should at least be closer to 2 when N_{AVG} is used (Lopez-Zamora et al., 2002). But, using both N_X and N_{AVG} in several species has given inconsistent results. In slash pine (*P. elliottii*), the coefficient was 1 when N_X from a small volume of soil was used (Escamilla et al., 1991). Young loblolly pine planted in spodosols had an improved relationship when root weight and depth were added to the model with N_X (coefficient = 1.4) (Adegbidi et al., 2004). In other species, the coefficient was significantly different from 2 even when N_{AVG} was used (Baldwin et al., 1971; Marriott, 1972; Lopez-Zamora et al., 2002). While the coefficient was not significantly different from 2 in windbreak grown cadaghi trees when N_{AVG} was used, the coefficient was significantly different from 2 when N_X was used. As small soil volume is one of the requirements for the relationship to be valid (Kendall and Moran, 1963; Melhuish and Lang, 1968), taking small soil volume may further improve this relationship. In another study, the coefficient was closer to 2 when a small volume of soil was considered (Schroder et al., 1996).

WB2 trees had the highest average L_V of the three windbreaks. The distribution of L_V with depth at 2 m from the windbreak generally corresponded with the root distribution at the same distance except for 30-40 cm depth in WB2 trees. WB4 trees having less number of roots compared to WB3 trees had the similar average L_V because of the differences in the sampling depth. Though root numbers were counted in grids up to 50 cm deep in all windbreaks, sampling for L_V was done to the depth of root presence, which was up to 40 cm in WB2, 50 cm in WB3 and 20 cm in WB4. L_V in WB4 trees was similar at both depths whereas it was highly variable in WB2 and WB3 trees. Compared to deeper soil, other studies have observed significantly greater L_V in surface soil (Peter and Lehmann, 2000; Moroni et al., 2003; Radersma and Ong, 2004; Coleman, 2007). Broadleaf species produced higher L_V than pine, and roots that were relatively small in diameter had greater L_V than larger diameter roots (Coleman, 2007). This has also been observed in *E. nitens* and *E. globulus* (Moroni et al., 2003).

Increased root weight can be expected with increased root density (Fabião et al., 1995; Pronk et al., 2002; Ruiz-Sánchez et al., 2005). WB2 trees which had the highest average root number also had the highest root weight. Root weight was also influenced by the presence of large roots. For example, despite having either equal or less number of roots in 0-10 cm compared to other depths in all three windbreaks, root weight was comparatively higher due to the presence of relatively more large roots. Root weight decreased with depth in five agroforestry trees in India (Das and Chaturvedi, 2008), but the windbreak trees did not show any pattern.

Non-native species are widely known for their competitive strength. Average root number and L_V in all three windbreak trees were 10 and 8 times less, respectively, compared to naturally established 5-year-old melaleuca (*Melaleuca quinquenervia*) in Florida (Lopez-Zamora et al., 2004). Since water uptake (Boyer, 1985), nutrient acquisition (Nye and Tinker, 2000) and soil respiration (Luo and Zhou, 2006) largely depend on L_V, windbreak grown cadaghi may be less competitive than melaleuca.

However, roots of citrus trees in flatwoods soils in Florida mostly grew horizontal and were concentrated in the upper soil layer (Morgan, 2006; Bauer et al., 2004; Calvert et al., 1977). As cadaghi roots were restricted in the upper 50 cm of soil and showed horizontal growth preference, there is a potential for competition between citrus trees and cadaghi trees if planted closer. If cadaghi trees compete with crops, root pruning can potentially reduce competition as cadaghi roots were generally in the upper 50 cm of the soil.

Conclusions

Because of the seepage irrigation at C&B Farms, the water table usually remained high in the field. High water table restricted root distribution to the top 50 cm of the soil. Older windbreak trees had significantly more roots. L_V and root weight distribution with depth were similar to that of root number. Cadaghi roots were anisotropic and showed horizontal growth preference. Both N_X and N_{AVG} were significant variables for estimating L_V. Assuming all roots in the grids were counted, N_X and N_{AVG} can be useful to estimate L_V in cadaghi. These results should be helpful to manage underground competition at the windbreak-crop interface where cadaghi trees are planted in field situations similar to C&B Farms. As the study is limited to one site, further research must be done to confirm and extend these results.

CHAPTER 5
BIOMASS ESTIMATION OF FAST-GROWING CADAGHI (*Corymbia torelliana*) WINDBREAKS IN FLORIDA

Introduction

Global interest in carbon sequestration by agroforestry systems increased after its recognition as a greenhouse gas mitigation strategy under the Kyoto Protocol (Albrecht and Kandji, 2003; Sharrow and Ismail, 2004; Nair et al., 2009). Such systems are becoming economic incentives for landowners with the increasing carbon markets (Oelbermann et al., 2004). Despite their carbon sequestration potential, agroforestry practices are not explicitly accounted for in national programs such as Forest Inventory Analysis of the US Forest Service and Natural Resources Inventory of the USDA Natural Resources Conservation Service (Perry et al., 2005). Agroforestry practices are also not included in many greenhouse gas mitigation reports (Schoeneberger, 2009).

Windbreaks are widely used in agroforestry across the globe. Besides primarily modifying microclimate and protecting crops, windbreaks provide multiple functions and/or products such as fruit, animal fodder, wildlife habitat, other economic and farm products and livestock odor mitigation (Tyndall and Colletti, 2007). With the increasing application of windbreaks, more trees and shrubs have been introduced in agricultural systems. Trees sequester carbon and store biomass as they grow. Therefore, introduction of trees has increased the carbon sequestration potential of agroforestry compared to monoculture crops (Kirby and Potvin, 2007). In addition to aboveground tree components, more than half of the carbon sequestered by trees is stored in the soil (Montagnini and Nair, 2004).

Most carbon sequestered in agricultural systems is quickly released back to the atmosphere. For efficient and effective carbon mitigation, it must be retained longer.

One way to retain carbon longer in plant biomass is by increasing the rotation age of trees and converting the wood to durable products after harvesting (Jose, 2009). Because agroforestry systems such as windbreaks and riparian buffers are planted for their long-term benefits and are not easily and quickly replaced by other practices (Schoeneberger, 2009), they can serve as the long-term carbon sinks.

Extensive work has been done on biomass estimation in forests as part of carbon mitigation programs, but carbon sequestered by agroforestry systems such as windbreaks is little studied (for example: Kort and Turnock, 1999; Zhou et al., 2007). Less competition and available nutrients in agroforestry systems favor growth and produce higher biomass. Both amount and rate of carbon sequestration can be greatly increased if fast-growing species are introduced. With the increasing use of fast-growing species such as eucalypts (*Eucalyptus grandis* and *E. amplifolia*) and cadaghi (Corymbia torelliana) in field windbreaks in Florida (Rockwood et al., 2008), both the amount and rate of carbon sequestration potential of Florida farms can be considerably increased. If carbon sequestered by windbreaks can be estimated, landowners could be compensated for the land occupied by the windbreak from carbon trading.

One challenge is to accurately estimate the biomass in agroforestry systems such as windbreaks due to a lack of standard methods and procedures. Because most woody biomass equations are developed from forest stands, such equations are inappropriate for estimating aboveground biomass in agroforestry systems (Nair et al., 2009). As trees in agroforestry systems are more open grown, biomass equations developed for forest stands underestimate biomass in agroforestry systems (Zhou, 1999) such as windbreaks. Therefore, the lack of predictive equations for trees grown in agroforestry systems hinders accurate estimate of carbon in agroforestry systems such as windbreaks and riparian buffers. For these agroforestry systems to be included in carbon accounting tools for agricultural lands (such as COMET VR [USDA NRCS, 2005] and C-Lock [Zimmerman et al., 2005]), separate equations need to be developed to give accurate biomass estimates for trees in agroforestry systems.

This study was conducted in southern Florida with the objectives to 1) develop biomass equations for windbreak grown cadaghi and 2) estimate oven-dry weight in various aged cadaghi trees in windbreaks.

Material and Methods

Study Area

The study was conducted at C&B Farms (26°27'30''N, 80°58'46"W) near Clewiston, Florida, where single-row cadaghi windbreaks of various ages ranging between 1 and 20 years were planted along primary irrigation channels (Figures 3-1 and 4-1), with ~1.5 m between the windbreaks and the channels. Soil was poorly drained Myakka sand (Sandy, siliceous, hyperthermic Aeric Haplaquods). The oldest cadaghi windbreak was planted in 1988, while the rest were planted in subsequent years. Some windbreaks were established and functional while others were in the early stages of establishment.

Tree Selection and Sampling

Five single-row windbreaks (WB) of various ages were selected for biomass estimation. Four windbreaks were established and functional (Table 5-1, Figures 3-1and 4-1) while the fifth, located north of windbreak WB1 in another field, was in the early stages of establishment. Five windbreak sections (~45 m long) were randomly selected in WB1-WB3 and WB5. In a shorter (length) windbreak WB4, only four sections were selected. Trees in the windbreak sections were measured for total height, diameter at breast height (DBH), tree spacing and height to crown ratio (Tables 5-1 to 5-3). Of 283 trees measured in the five windbreaks, approximately 25 and 33% were 10-20 and 20-30 cm in DBH, respectively. Few trees were >50 cm in DBH (3.2%). The number of trees 5-10 m tall was the highest (44.2%) followed by 15-20 m (19.8%).

Table 5-1. Number of trees (n), age (years), height (m), diameter at breast height (DBH, cm), spacing between trees (m) and height to crown ratio (H:C) of five single-row cadaghi windbreaks at C&B Farms used for biomass sampling (mean value ± standard error)

Windbreak	Age	Height	DBH	Spacing	H:C
WB1 (n=64)	20	17.5±0.2	40.6±1.2	2.5±0.1	1.3
WB2 (n=51)	8	10.3±0.2	24.6±0.7	4.9±0.1	1.1
WB3 (n=72)	6	8.0±0.1	17.9±0.4	3.3±0.1	1.1
*WB4 (n=37)	8	10.0±0.2	24.9±0.7	4.5±0.2	1.2
WB5 (n=59)	2	4.3±0.7	7.9±0.3	3.9±0.1	1.0

Measured in December 2007; *Measured in September 2008.

Table 5-2. Number of trees by diameter at breast height (DBH) class (cm) in five cadaghi windbreaks at C&B Farms (number of trees selected for further sampling in parentheses)

DBH class	WB1	WB2	WB3	WB4	WB5	Total
≤10	0	0	2	0	50 (1)	52
10-20	1	9	48 (2)	5	9	72
20-30	6	36 (2)	22 (1)	29 (2)	0	93
30-40	26 (1)	6 (1)	0	3	0	35
40-50	22 (1)	0	0	0	0	22
>50	9	0	0	0	0	9
Total	64	51	72	37	59	283

Table 5-3. Number of trees by height class (m) in five cadaghi windbreaks at C&B Farms (number of trees selected for further sampling in parentheses)

Height class	WB1	WB2	WB3	WB4	WB5	Total
≤5	0	0	2	0	50	52
5-10	0	24	70 (3)	22 (1)	9 (1)	125
10-15	7	27 (3)	0	15 (1)	0	49
15-20	56 (2)	0	0	0	0	56
>20	1	0	0	0	0	1
Total	64	51	72	37	59	283

Trees in all windbreaks were first grouped into DBH classes. Eleven trees were then randomly selected based on the DBH distribution and destructively sampled: 1, 2, 5, 2 and 1 trees from each of the ≤10, 10-20, 20-30, 30-40, and 40-50 cm DBH classes, respectively were selected (Table 5-2). Relatively more sample trees were selected from DBH classes with more trees. Since larger trees were mostly in WB1, which had wide irrigation channels on either side making access limited, trees >50 cm DBH were not included in the sample.

Height and DBH of sample trees were measured before felling. Trees were then cut at ground level. The crown was divided into two equal parts: upper and lower crown. Crown (including branch and leaf) weight was estimated using randomized branch sampling (RBS; Valentine et al., 1984; Gregoire et al., 1995). In RBS, the trunk as well as branches above a threshold diameter are considered branches. A segment is defined as the part of the branch between two consecutive nodes. A sequence of connected branch segments forms a path. Two paths were randomly selected in each crown section. The selection probability assigned to each branch at a node was $D^{2.67}$ (where D is the diameter) divided by the sum of the $D^{2.67}$ values of all branches emanating from the node. Cumulative selection probabilities were calculated for branches at each node. Then a random number was generated between zero and one using Microsoft Excel, the branch with the cumulative selection probability larger than the random number was selected, and the path continued into another segment. The process was repeated until a terminal branch with a diameter of 2.5 cm was obtained for trees with DBH>10cm. Where trees had DBH < 10 cm, the branch diameter of 2 cm was taken as terminal. The terminal branch, i.e. the sample branch, was cut off and collected. Leaves in the sample branch were excised and separate fresh weights of leaf and branch were taken in the field. The samples were transported to the lab and oven dried at 55° C for about a month until constant weights were obtained. Segments associated with epicormic shoots and branches smaller than the threshold branch size along the path were noted and collected separately. Dry weights of sample branches and leaves from each path were used to estimate tree-level oven-dry crown weights using the inflation factors obtained from the cumulative probabilities. Four crown weight estimates were obtained for each tree from each of four paths. The average of the four crown estimates was calculated for each tree to obtain an unbiased crown weight estimate per tree (Gregoire et al., 1995). Estimates from the four paths were considered independent as the interest was in tree weight prediction rather than statistical testing.

To estimate trunk weights, outside bark diameter measurements were taken at the base and then every 1.5 m along the trunk until a 2.5 cm diameter was reached. A sample disk was collected from the base and the top of each 1.5 m section. Fresh weights of the discs were taken immediately in the field. The discs were brought to the lab and soaked in water for 24 hours. After 24 hours, the discs were removed from water and excess water was wiped off. Their volume was determined using the water displacement method (Ilic et al., 2000). The discs were then oven dried at 55° C for about a month until a constant dry weight was obtained. Density of the disks was estimated in kg/m^3 as described in Ilic et al. (2000). Density of each 1.5 m stem section was calculated as the average of the densities of the lower and upper disk of the section.

Outside bark volume of each 1.5 m trunk section was estimated using the conic frustum equation:

$$V = \frac{1}{12}\pi\, l \left(\frac{D_1^2 + D_1 D_2 + D_2^2}{10000} \right) \qquad (5\text{-}1)$$

where V is the volume (m^3), l the segment length (m), D_1 the outside bark diameter of the lower disk (cm) and D_2 the outside bark diameter of the upper disk (cm).

Oven-dry weight of each 1.5 m trunk section was estimated by multiplying the section volume by the average density of the section. Total trunk dry weight was estimated as the sum of the dry weights of all the trunk sections. Trunk and crown weight was added to obtain the whole tree weight.

Development of Biomass Equations

Plots of crown, trunk and whole tree weights against DBH and height were nonlinear (Figures 5-1 and 5-2). Therefore, various nonlinear equations (5-2 to 5-6) were fit using the SAS procedure PROC NLIN (SAS Institute Inc., 2008).

$$Y = b_1 X^{b2} \qquad (5\text{-}2)$$

$$Y = b_3 X / b_4 + X \qquad (5\text{-}3)$$

$$Y = b_5 X^{b6X} \qquad (5\text{-}4)$$

$$Y = b_7 b_8^X \qquad (5\text{-}5)$$

$$Y = b_9 e^{b10X} \qquad (5\text{-}6)$$

where Y is the oven-dry weight of the whole tree or tree component (crown or trunk), X the predicting variable (DBH or combinations of DBH and height), and b_1-b_{10} are model parameters to be estimated.

The root mean square error (RMSE) was calculated for each model, as well as the coefficient of determination (R^2). Model 5-2, which had the lowest RMSE, highest R^2 and best fit plots was selected.

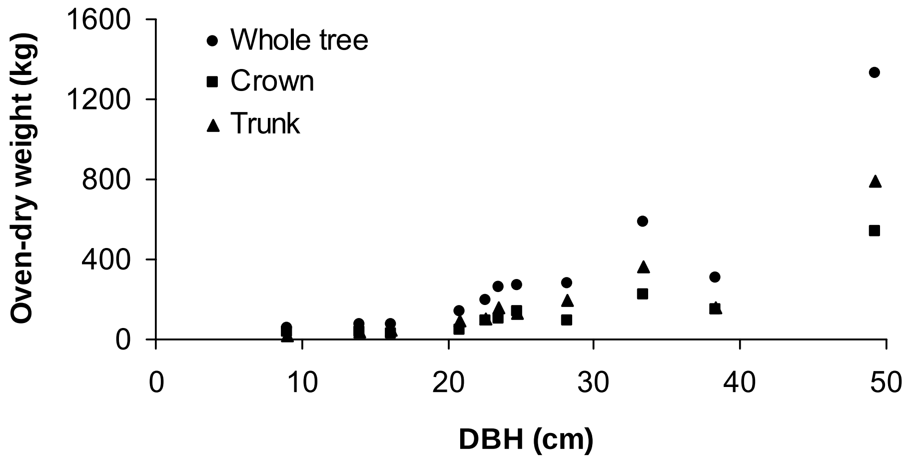

Figure 5-1. Aboveground oven-dry weight (kg) vs. diameter at breast height (DBH) of 11 cadaghi sample trees at C&B Farms.

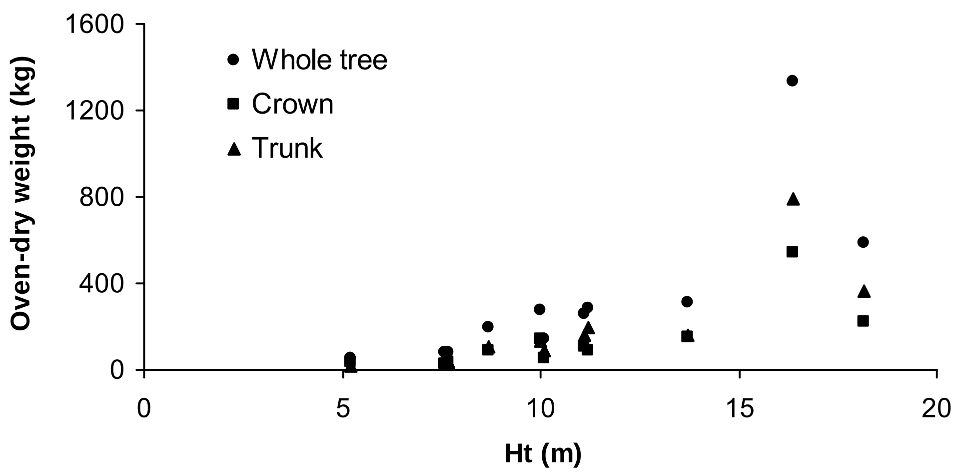

Figure 5-2. Aboveground oven-dry weight (kg) vs. height of 11 cadaghi sample trees at C&B Farms.

Two sets of equations, one with only DBH and another with both DBH and height as predictors, were considered. Several combinations of DBH and height were considered in the model. Models that gave the lowest RMSE, highest R^2 and best fit plots were selected. The best DBH-based equations were:

$$Y_C = b_{11} DBH^{b12} \quad (5\text{-}7)$$

$$Y_T = b_{13} DBH^{b14} \quad (5\text{-}8)$$

$$Y_{WT} = b_{15} DBH^{b16} \quad (5\text{-}9)$$

where Y is the oven-dry crown (C), trunk (T) and whole tree (WT) weight (kg), DBH the diameter at breast height (cm), and b_{11}-b_{16} the parameters to be estimated.

The DBH- and height-based equations estimated were:

$$Y_C = b_{17} (DBH^2 H_T)^{b18} \quad (5\text{-}10)$$

$$Y_T = b_{19} (DBH \ \ H_T)^{b20} \quad (5\text{-}11)$$

$$Y_{WT} = b_{21} (DBH^2 H_T)^{b22} \quad (5\text{-}12)$$

where Y is the oven-dry crown (C), trunk (T) and whole tree (WT) weight (kg), DBH the diameter at breast height (cm), H_T the total tree height (m), and b_{17}-b_{22} the parameters to be estimated.

For ease of fitting the models, nonlinear models were linearized through logarithmic transformations. Equations 5-13, 5-14, 5-15, 5-16, 5-17 and 5-18 were obtained from logarithmic transformation of equations 5-7, 5-8, 5-9, 5-10, 5-11 and 5-12, respectively.

$$\ln Y_C = \ln c_1 + c_2 \ln DBH \quad (5\text{-}13)$$

$$\ln Y_T = \ln c_3 + c_4 \ln DBH \quad (5\text{-}14)$$

$$\ln Y_{WT} = \ln c_5 + c_6 \ln DBH \quad (5\text{-}15)$$

$$\ln Y_C = \ln c_7 + c_8 \ln(DBH^2 H_T) \quad (5\text{-}16)$$

$$\ln Y_T = \ln c_9 + c_{10} \ln(DBH \ \ H_T) \tag{5-17}$$

$$\ln Y_{WT} = \ln c_{11} + c_{12} \ln(DBH^2 H_T) \tag{5-18}$$

where ln is the natural logarithm, *Y* the oven-dry crown (*C*), trunk (T) and whole tree (*WT*) weight (kg), *DBH* the diameter at breast height (cm), H_T the total tree height (m), and c_1-c_{12} the parameters to be estimated.

Predictions from nonlinear and logarithmic equations were compared to see if the sum of the predicted tree component weights was equal to the predicted whole tree weight and which model gave the closest estimation to the observed whole tree weight (Table 5-4). The sum of predicted tree component weights was similar to predicted whole tree weight only when the same combinations of predicting variables, i.e. DBH^2H_T, was used for crown, trunk and whole tree weight prediction in nonlinear equations. When DBH H_T was used as predicting variable for trunk weight (model 5-11) and DBH^2H_T for crown and whole tree (models 5-10 and 5-12), the sum of predicted tree components was not similar to predicted whole tree weight. Logarithmic transformed equations (5-16 to 5-18) also did not have the additive property. However, mean tree weight predicted from logarithmic equations (309.3 kg) was closer to the mean of the observed whole tree weights (326.4 kg). Median weight of observed tree was 262 kg. Nonlinear model underpredicted tree weight when the weight was below the median, but the prediction of logarithmic model was closer to the observed value (Figure 5-3). This suggested that the logarithmic model was better than the nonlinear model for smaller trees. All windbreaks except WB1 were younger than 8-year-old. Therefore, logarithmic models were selected to predict the biomass. However, nonlinear model can be used for predicting biomass in older windbreak trees.

Table 5-4. Comparison of predicted whole tree weight (kg) and additive property of nonlinear and logarithmic models (model number that was used to predict the weights in parentheses).

Windbreak	Observed	Non-linear model			Logarithmic model	
		Whole tree (5-12)	Crown (5-10) +Trunk (5-11)	Crown (5-10) +Trunk*	Whole tree (5-18)	Crown (5-16) + Trunk (5-17)
WB1	584.1	594.4	663.5	594.5	549.3	610.4
WB1	1334.3	1245.1	1228.8	1244.9	871.5	886.8
WB2	262.0	161.3	152.4	161.4	243.3	245.4
WB2	139.4	111.5	103.3	111.6	193.2	193.5
WB2	310.2	589.6	560.8	589.6	546.5	545.2
WB3	76.6	34.9	30.9	35.0	93.6	93.1
WB3	78.6	46.7	40.2	46.8	112.2	109.0
WB3	194.6	113.5	97.5	113.6	195.4	186.1
WB4	273.9	161.9	144.9	162.0	243.8	237.3
WB4	282.5	242.5	222.8	242.7	313.8	309.0
WB5	54.8	8.7	7.1	8.7	39.2	38.5
Mean	326.4	300.9	295.6	301.0	309.3	314.0

*Trunk biomass was predicted using the model $Y=b_1\ (DBH^2H_T)^{b2}$.

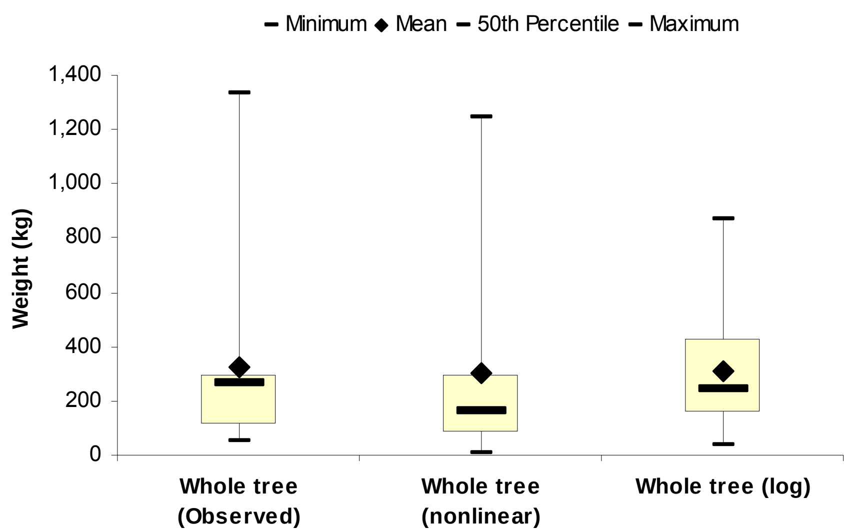

Figure 5-3. Box plot of observed whole tree weights and weights estimated from nonlinear (5-12) and logarithmic (5-18) models.

Data were fitted using the logarithmic transformed equations. Because of the limited number of samples, judging the homoscedasticity of the residuals from the logarithmic transformed models from plots was difficult. Therefore, White's test was performed in the PROC REG procedure to test the homogeneity of error variance. The

PROC UNIVARIATE procedure was used to test the normality of residuals. However, constant error variance and normal residuals could not be obtained from equation 5-14. Therefore the equation was not used and only the equation with DBH and height (5-17) was used for estimating trunk weight. The unsigned deviation (δ), also known as error of estimate, was also calculated for each model using the back transformed data as follows:

$$\delta = \frac{\sum_{i=1}^{n}[(|\,\text{Observed} - \text{Predicted}\,|)/\text{Observed}]}{\text{n}}\, x\, 100 \qquad (5\text{-}19)$$

where n was the sample size.

Biomass Estimation in Windbreaks

The final logarithmic transformed equations were used to estimate oven-dry weights of trees in the windbreaks using tree variables from 45 m long windbreak sections. Because back transformation of estimates from logarithmic model added systematic bias leading to underestimation of weight (Baskerville, 1972), adjustments were made to final estimates by multiplying the estimates by correction factor (Sprugel, 1983). The correction factor was calculated using following equations:

$$SEE = \sqrt{\sum (\log y_i - \log \hat{y}_i)^2 / (n-2)} \qquad (5\text{-}20)$$

where SEE is the standard error of estimate, y_i the value of the ith dependent variable $\hat{y}_i$ the corresponding the ith predicted values and n the number of samples. Then the correction factor, *CF*, was calculated as:

$$CF = \exp(SEE^2 / 2) \qquad (5\text{-}21)$$

Estimated oven-dry weight in five windbreaks was expressed in kg weight/100 m windbreak length.

Results

Biomass Allocation in Tree Components

Heights and DBHs of sample trees ranged from 5.2 to 18.2 m and 9.0 to 49.3 cm, respectively (Table 5-5). Almost all smaller trees were from WB3 and WB5, which had more than 44% weight on average in the tree crown, whereas larger trees from WB1, WB2 and WB4 had less than 42% weight in the tree crown on average. Whole tree weights generally increased with DBH. Crown and trunk weights averaged over all sample trees were 45.5 and 55.5%, respectively.

Table 5-5. Height (m), diameter at breast height (DBH, cm), and oven-dry crown, trunk and whole tree weights (kg) of 11 cadaghi sample trees at C&B Farms (percentages in parentheses).

Windbreak	Height	DBH	Crown	Trunk	Whole tree
WB1	18.2	33.4	220.4 (37.7)	363.7 (62.3)	584.1
WB1	16.4	49.3	541.6 (40.6)	792.7 (59.4)	1334.3
WB2	10.1	20.8	50.9 (36.5)	88.5 (63.5)	139.4
WB2	11.1	23.5	102.4 (39.1)	159.6 (60.9)	262.0
WB2	13.7	38.3	147.9 (47.7)	162.3 (52.3)	310.2
WB3	7.7	14.0	38.8 (50.7)	37.7 (49.3)	76.6
WB3	7.6	16.1	29.6 (37.7)	49.0 (62.3)	78.6
WB3	8.7	22.6	89.1 (45.8)	105.5 (54.2)	194.6
WB4	10.0	24.8	142.4 (52.0)	131.5 (48.0)	273.9
WB4	11.2	28.2	91.4 (32.4)	191.1 (67.6)	282.5
WB5	5.2	9.0	38.2 (69.7)	16.6 (30.3)	54.8

Allometric Biomass Equation Fitting

Equations 5-13 to 5-18 (except 5-14) were fitted using the destructively sampled data. Parameters and fit statistics from the logarithmic equations are given in Table 5-6. The DBH-based equation was sufficient to predict the crown weight; adding height in the equation did not change the precision of crown weight estimate. For trunk weight, acceptable residual plots were obtained only when height was incorporated into the equation. For whole tree weight estimation, adding height increased the coefficient of determination (R^2) slightly, from 0.89 to 0.90.

Table 5-6. Parameter estimates, mean square error (MSE), coefficient of determination (R^2), unsigned deviation (δ) and P-value from logarithmic transformed biomass equations for windbreak grown cadaghi trees at C&B Farms.

Component	Equation	$\ln b_1$	b_2	MSE	R^2	δ (%)	*P-value*
DBH-based equation							
Crown	5-13	-0.49	1.60	0.17877	0.79	38	0.0003
Whole tree	5-15	-0.42	1.84	0.10891	0.89	28	<.0001
DBH- and Height-based equations							
Crown	5-16	-0.53	0.60	0.17696	0.79	36	0.0003
Trunk	5-17	-2.06	1.25	0.07872	0.93	20	<.0001
Whole tree	5-18	-0.50	0.68	0.09932	0.90	25	<.0001

It was difficult to clearly see the homogeneity of error variance in the residual plots because of the limited number of data points. However, the Shapiro-Wilk (W) test for normality of errors and White's test for homogeneity of error variance gave satisfactory results for all the equations (Table 5-7). The absolute percentage of deviation (□) ranged between 20 and 38% (Table 5-6), but predicted values in logarithmic transformed models did not markedly deviate from the observed values (Figures 5-4, 5-5 and 5-6).

Table 5-7. Test statistics for normality and homogeneity of error variance of logarithmic transformed models for windbreak grown cadaghi trees at C&B Farms.

Component	Equation	Normality test		White's test		
		Shapiro-Wilk (W)	P-value	DF	χ^2	P-value
DBH-based equation						
Crown	5-13	0.949	0.6387	2	2.47	0.2910
Whole tree	5-15	0.964	0.8228	2	5.99	0.0500
DBH- and Height-based equation						
Crown	5-16	0.940	0.5218	2	2.19	0.3354
Trunk	5-17	0.883	0.1143	2	2.66	0.2641
Whole tree	5-18	0.979	0.9601	2	4.44	0.1088

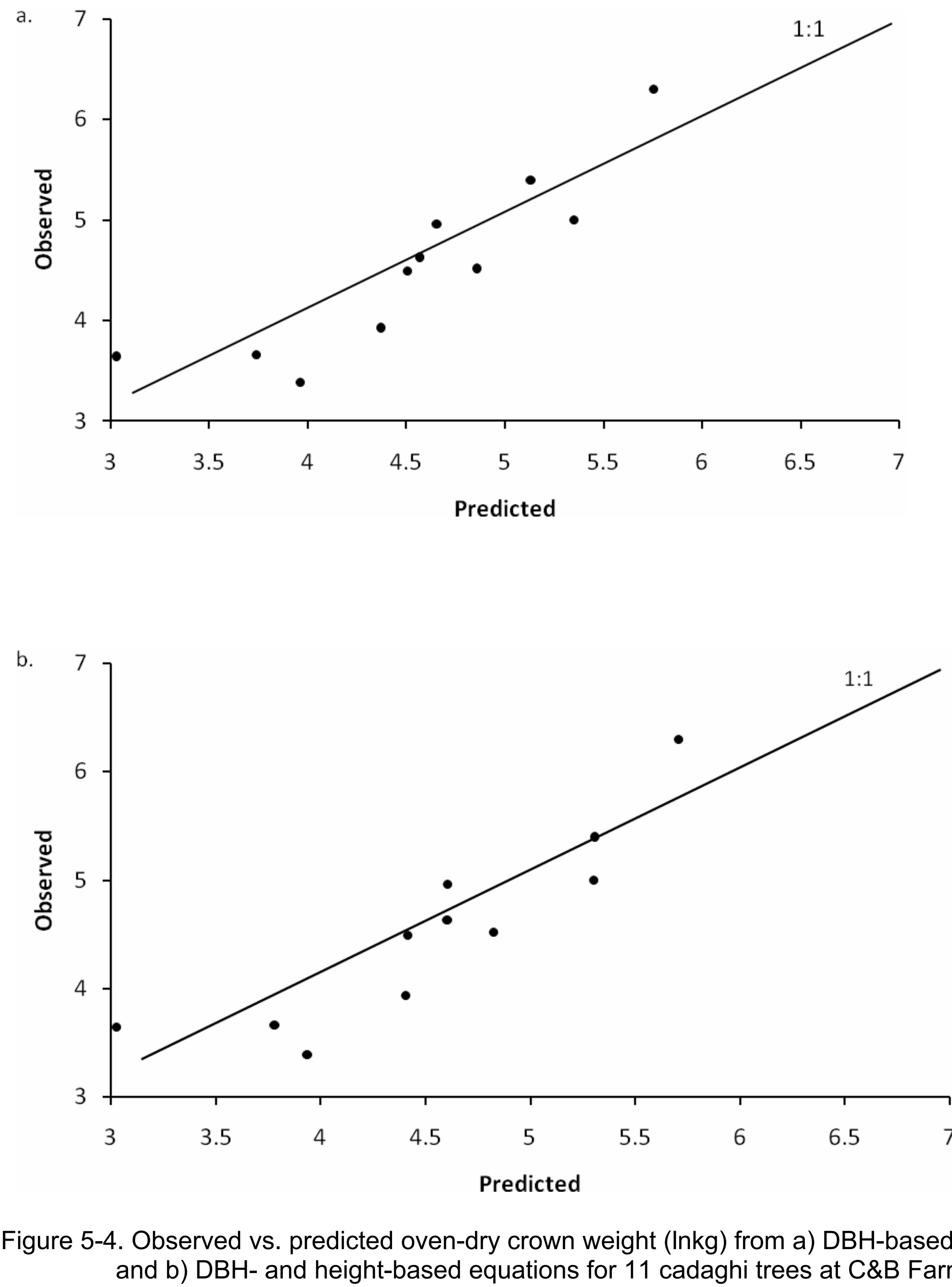

Figure 5-4. Observed vs. predicted oven-dry crown weight (lnkg) from a) DBH-based and b) DBH- and height-based equations for 11 cadaghi trees at C&B Farms.

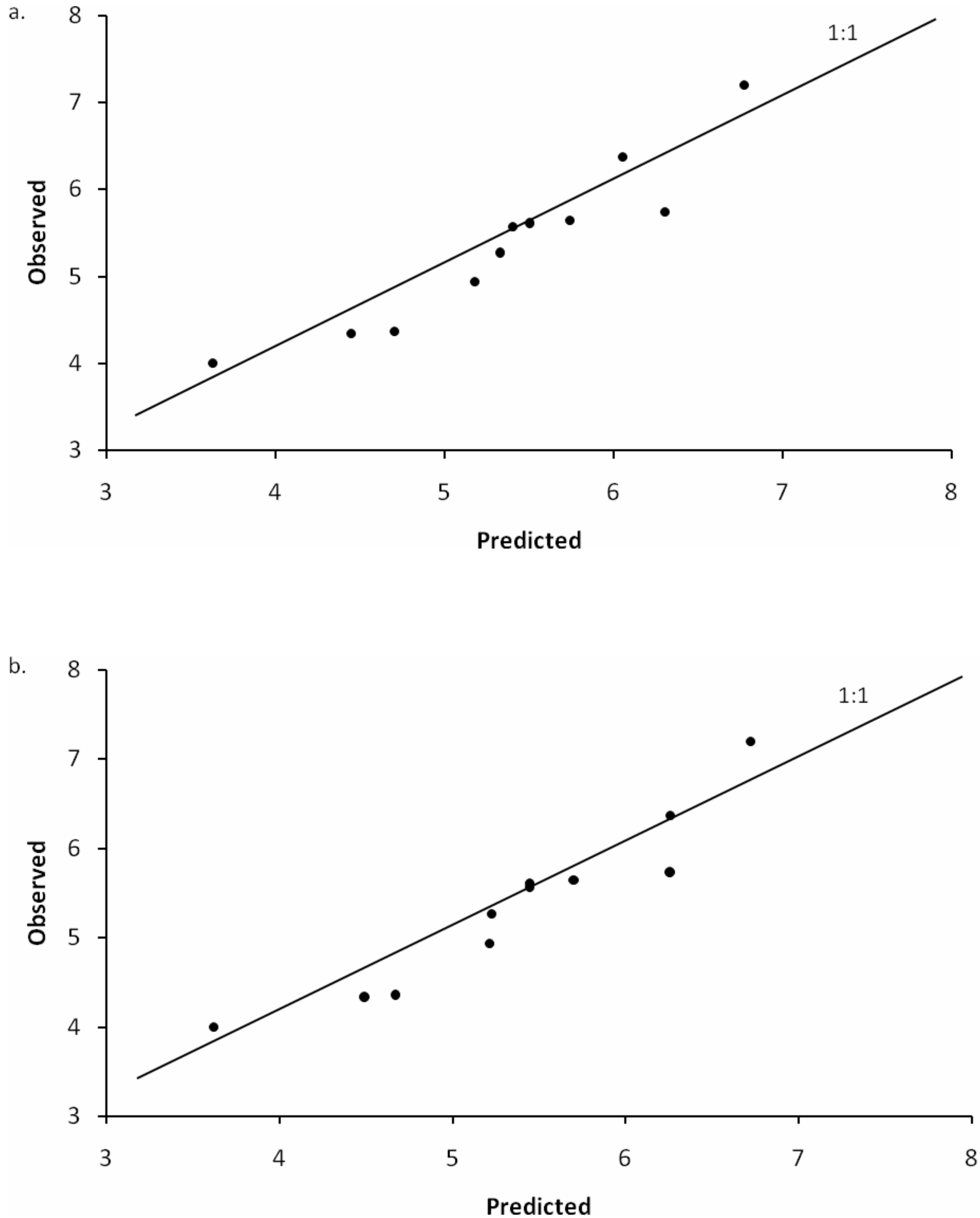

Figure 5-5. Observed vs. predicted oven-dry whole tree weight (lnkg) from a) DBH-based and b) DBH- and height-based equations for 11 cadaghi trees at C&B Farms.

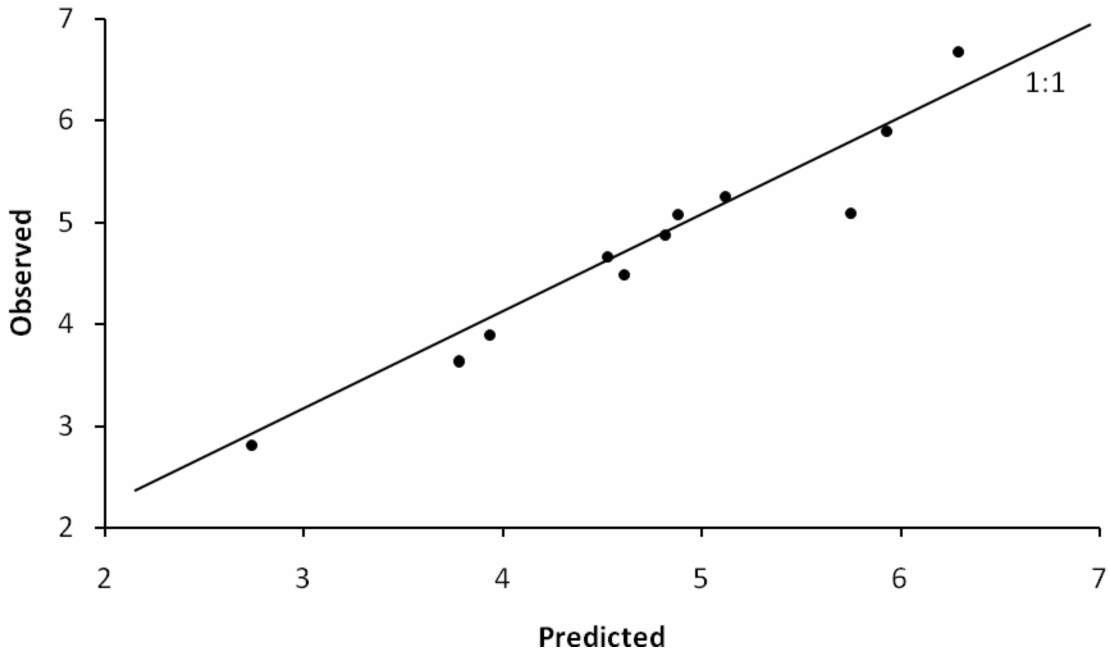

Figure 5-6. Observed vs. predicted oven-dry trunk weight (lnkg) from DBH- and height-based equation for 11 cadaghi trees at C&B Farms.

Biomass in Windbreaks

The logarithmic equations were used to estimate oven-dry tree weights in the five cadaghi windbreaks. DBH- and height-based equations gave smaller standard errors for average weight/tree in the first four windbreaks (Table 5-8), but both DBH-based, and DBH- and height-based equations gave similar errors for WB5. Weight partitioning into crown and trunk varied among windbreaks (Tables 5-8 and 5-9). Young windbreaks had relatively more weight in the crown than in the trunk and relative trunk weights increased with age. For example, crown weight was approximately 58% of the whole tree weight in WB5 whereas it was approximately 39% in WB1 trees. In WB3 trees, both crown and trunk weights were similar. DBH-based equations generally estimated relatively more crown and whole tree weights in all windbreaks except for WB1 trees in which DBH- and height-based equation estimated more crown and whole tree weight.

Table 5-8. Number of trees (n) and average oven-dry weight (kg/tree ± standard error) estimated using the logarithmic transformed equations in five cadaghi windbreaks at C&B Farms.

Windbreak	DBH-based equations		DBH- and height-based equations		
	Crown	Whole tree	Crown	Trunk	Whole tree
WB1 (n=64)	285±12	668±37	273±10	481±19	708±29
WB2 (n=51)	116±6	264±14	112±5	137±8	253±13
WB3 (n=72)	70±3	147±6	67±2	68±3	138±5
WB4 (n=37)	117±5	266±14	111±4	131±6	248±11
WB5 (n=59)	19±1	33±2	18±1	12±1	31±2

Whole tree weight/100 m windbreak length ranged from 802 to 20,145 kg in WB5 and WB1 trees, respectively (Table 5-9). Crown weight ranged from 470 to 7,759 kg, and trunk weight ranged from 307 to 13,687 kg in WB5 and WB1, respectively. The smallest differences in crown and whole tree weight/100 m windbreak length estimated from the DBH, and DBH- and height-based equations were in WB5 trees, but WB1 trees had the largest difference both for crown and whole tree weight. The difference in crown and whole tree weights in WB5 trees was 31 and 73 kg, respectively. In WB1 trees, the difference was 409 and 1,148 kg for crown and whole tree weights, respectively.

Table 5-9. Number of windbreak sections (n) and oven-dry weight (kg/100 m windbreak length ± standard error) estimated using the logarithmic transformed equations in five cadaghi windbreaks at C&B Farms.

Windbreak	DBH-based models		DBH- and height-based models		
	Crown	Whole tree	Crown	Trunk	Whole tree
WB1 (n=5)	7,350±537	18,997±1,316	7,759±728	13,687±1,418	20,145±1,815
WB2 (n=5)	2,620±338	5,980±864	2,533±305	3,100±451	5,727±774
WB3 (n=5)	2,225±126	4,695±300	2,130±135	2,167±185	4,437±316
WB4 (n=4)	2,403±188	5,472±457	2,272±166	2,695±218	5,107±397
WB5 (n=5)	501±42	875±79	470±36	307±27	802±68

Discussion

Larger trees generally had more trunk weight whereas smaller trees had relatively more crown weight. This was primarily due to competition between trees in the windbreak. Young trees had relatively more space to grow and they also received sunlight from all sides as they were in north-south oriented windbreaks. As the crown starts closing in, trees compete for light and growing space. Branches in the shaded area in some trees self prune because of lateral shading and crowns of trees grown in such environments tends to be narrower and shorter. Foliage was generally concentrated in the upper part of the canopy in shade grown trees (Mar:Mohler, 1947) and branchwood production was also low (Dicus and Dean, 1998). On the other hand, trees grown in sparser stands had wider and longer crowns with numerous large lower branches (Dean and Baldwin, 1996). Compared to open grown *Abutilon theophrasti*, Henry and Thomas (2002) also observed reduced leaf weight and leaf area in shade grown plants because of lateral shading and the height of shade grown plants increased by 33%. This phenomenon was commonly observed in shade grown plants (Henry and Aarssen, 1997). As height increased, relative allocation of trunk weight also increased (Osada et al., 2004). Dossa et al. (2008) also observed relatively higher weight fractions in open-grown coffee (*Coffea canephora* var *robusta*) trees compared to shade grown coffee.

One of the significant factors for higher crown weight in younger windbreak trees is the orientation of the windbreaks. Both WB3 and WB5 (younger windbreaks) are oriented north-south whereas the older windbreaks are oriented east-west. All the destructively sampled larger trees were from east-west oriented windbreaks. Because of the orientation, trees in north-south oriented windbreaks received sunlight from all sides throughout the day. Lateral shading in north-south oriented windbreaks is minimal compared to east-west oriented windbreaks. The height to crown ratio of the trees in the windbreaks (Table 5-1) also suggests that north-south oriented windbreaks (WB3 and

WB5) have longer crowns, which could potentially have more branches and leaves compared to east-west oriented windbreaks.

Easily measured DBH and height were used to develop biomass equations to estimate tree weights in windbreaks. DBH alone gave satisfactory results for crown and whole tree weight prediction. Though height was not an important variable for crown weight estimation, its addition in the model gave better results for the whole tree weight estimate. Both DBH and height were required for trunk weight prediction. DBH is the most commonly used variable in estimating trunk and whole tree weight, and is usually measured in large scale National Forest Inventories. However, others have suggested using both the DBH and height for large scale applications (Jenkins et al., 2003; Lambert et al., 2005). Therefore, both DBH-based and DBH- and height-based equations are generally developed for most species. DBH alone gave satisfactory results, but height was a secondary variable for trunk weight estimation (Lambert et al., 2005), and it brought additional information in addition to DBH (Joosten et al., 2004; Vallet et al., 2006). Including height increased the precision of estimates but this precision was obtained at the added cost of measuring height (Zhou et al., 2007). However, acceptable fit plots were obtained only when height was incorporated in the trunk biomass model indicating that the use of only DBH in the trunk weight estimation of windbreak grown cadaghi may be insufficient. DBH was an essential variable for crown weight estimation but height was less important (Lambert et al., 2005). The current result also supports this observation.

Instead of using DBH directly, stem cross sectional area (SCSA) and circumference at breast height was used for biomass estimation in agroforestry systems in some studies. In prairie windbreaks in Canada, SCSA at 1.3 m was the best predictor for aboveground weight in deciduous and coniferous species. Including height did not improve the relationship (Kort and Turnock, 1999). Stem circumference at 1.3 m and basal circumference (at 0.40 m) were the best weight predictors for *Albizia adianthifolia* grown as shade tree in shaded coffee agroforestry system in Togo (Dossa et al., 2008). For weight estimation of open grown juvenile tropical tree species, the number of leaves in the crown, height and basal diameter have also been used as predictors (Menalled and Keltry, 2001).

Fast-growing species such as cadaghi can efficiently sequester carbon compared to other windbreak species. For example, Zhou et al. (2007) estimated weights of three Russian-olive windbreaks in eastern Montana planted in single-row and double-row with Siberian peashrub (*C. arborescens*). The age of the windbreaks ranged between 15 and 53 years, and the estimated whole tree weight ranged between 1,744 and 4,957 kg/100 m windbreak length for 15 and 39-year-old windbreaks. Estimated whole tree weight for a 53-year-old windbreak was only 3,636 kg/100 m windbreak length. However, the whole tree weight of 8-year-old cadaghi windbreak in the current study exceeds the maximum whole tree weight observed for Russian-olive tree windbreak. Kort and Turnock (1999) reported mean aboveground weight between 161.8 to 544.3 kg/tree for eight different species with ages between 33 and 53 years. The maximum weight of 544.3 kg/tree for 33-year-old hybrid poplar was still less than the average weight/tree observed in WB1 trees in the current study.

Conclusions

Both DBH and height were useful in estimating weights of cadaghi windbreak trees. Though DBH alone was sufficient for estimating crown weight, adding height gave better results for whole tree weight. Height was an important variable for estimating trunk weight. Fast-growing cadaghi windbreaks can sequester significantly more carbon than other species while providing wind speed reduction and microclimate modification at the same time. Such systems can provide higher returns to landowners if carbon credits can be traded.

CHAPTER 6
CONCLUSIONS

Live windbreaks are a widely used agroforestry practice which increases crop yield and quality and at the same time provides several ecosystem services and environmental benefits. Increased farm production from wind reduction and microclimate modification are some of the direct benefits. Indirect benefits include ecosystem services and environmental benefits such as carbon sequestration, biodiversity conservation, soil enrichment and air and water quality (Jose, 2009). This study assessed wind reduction and microclimate modification by single-row eastern redcedar and cadaghi windbreaks in Florida farms. Root distribution in various aged cadaghi windbreaks and their carbon sequestration potential was also documented.

Summary of Results

Windbreak Function and Microclimate Modification

Single-row windbreaks of eastern redcedar and cadaghi effectively reduced wind and modified microclimate on the leeside. Maximum wind reduction was recorded closer to the windbreak, but wind reduction gradually decreased at locations away from the windbreak. Low porous windbreaks (redcedar and cadaghi WB1) reduced more wind than cadaghi windbreak WB2, which was porous of all windbreaks studied. Wind speeds at two times the windbreak height (2H) south of redcedar and cadaghi windbreak WB1 were generally less than 18% and 30% of the open wind speed, respectively, when the wind direction was nearly perpendicular to the windbreaks. These values were equivalent to the porosities of the respective windbreaks, suggesting that these windbreaks are as effective as multiple-row windbreaks of other species. The minimum wind speed was recorded at 6H north of relatively porous cadaghi windbreak

WB2. Windbreaks also reduced wind during a tropical storm. The minimum average wind speed was recorded at 2H north of cadaghi windbreak WB2 (~74%) and at 4H west of WB3 (~52%). Wind speed at 23H north of cadaghi windbreak WB2 was 90% and at 12H west of WB3 was 80% of the open wind speed. Along with wind reduction, windbreaks also modified microclimate. Microclimate modification varied with the time of the day and the location on the leeside of the windbreaks. Windbreaks also lowered temperature up to 1.9° C during cold fronts indicating that crops on the leeside of low porous windbreaks are susceptible to freeze damage during such events.

Root Distribution

Older cadaghi windbreaks had significantly more roots. Roots were generally in the surface soil, and all were smaller than 20 mm in diameter. More than 50% of the roots were present in the upper 20 cm of soil in all windbreak trees. Because of the high water table in the area, roots were restricted to upper 50 cm of the soil. Cadaghi roots were anisotropic and showed horizontal growth preference. Roots were ranked $N_X > N_Y > N_Z$ (N_X, N_Y and N_Z are number of roots exiting the frontal face of the trench wall, vertical face perpendicular to the trench wall and the basal horizontal face, respectively) in all three windbreak trees individually and when data from three windbreaks were combined. Root length density (L_V) was also higher in older windbreak trees and its distribution with depth was similar to N. Number of roots exiting the frontal face of the trench wall (N_X) and average root number (N_{AVG}) measured in three-dimensions (X, Y and Z) of the soil cubes were significant for predicting L_V. The N coefficient was significantly different from 2 when N_X was used, but was not significantly different when N_{AVG} was used. Root weight was also higher in older windbreak trees.

Biomass Estimation

Smaller cadaghi trees had slightly higher crown weight compared to larger trees (44% vs. 42%). Separate DBH-based and DBH- and height-based weight equations gave acceptable crown, trunk and whole tree weight predictions. R^2 ranged between 0.79 and 0.93 for different tree components. DBH was sufficient for crown and whole tree weight prediction, but height was an important variable for trunk weight prediction. Average weight/tree in a windbreak ranged from 31 to 708 kg for 2-year-old and 20-year-old windbreaks, respectively. A 100 m length of 20-year-old windbreak had 20,145 kg of oven-dry weight, whereas a 2-year-old windbreak had 802 kg.

Future Research

Extensive research has been done on wind reduction and microclimate modification by tree windbreaks. However, there are only limited studies on root distribution and biomass estimation in windbreaks. Though the results of the current study are generally in agreement with other studies, there are still many questions that need to be addressed.

- Cadaghi is a good windbreak species, but is relatively a new species for Florida. Available information suggests that cadaghi is cold intolerant. Therefore, it may not be a suitable species for parts of Florida, where temperatures fall below freezing point in winter. Newly planted windbreaks must be closely observed and regularly monitored. Field trials should be conducted to confirm its suitability for other parts of Florida.

- Non-native species are usually highly competitive. However, this study and others (Sun and Dickinson, 1997; Nissen et al., 1999) provide limited information on cadaghi root distribution and its competitive strength. The results of this study may not be widely applicable because of the lack of site replications and unique field conditions such as location of trees along irrigation channels and high water table. Trees planted in different soil types and environments should be studied to get wider understanding of its root architecture and distribution.

- Cadaghi roots showed horizontal growth preference and roots were restricted in the top 50 cm of the soil. Cadaghi can potentially compete with crops in flawtwoods soil where roots are concentrated in the upper soil layer (e.g. citrus). Therefore, its competitive potential should be studied.

- One of the requirements for windbreak trees is the ability to withstand high winds. This is very important for windbreaks in Florida as the state experiences frequent tropical storms and hurricanes. Cadaghi trees in the study area have suffered minimal damage during previous storms, but the current study does not identify why they are windfirm and warrants further investigation. Eucalypts trees generally had higher root density under the stump (Laclau et al., 2001; Bouillet et al., 2002). As cadaghi is closely related to eucalypts, new research should focus in areas closer to the stump.

- Biomass equations presented here are developed from 11 destructively sampled cadaghi trees, and their wider application is limited. However, this is a good first approximation given that these trees have a limited planting distribution in Florida. Cadaghi has now been planted in other areas in central and south Florida. In the future, more samples from a larger geographical area will be needed to fully calibrate these equations.

- Though cadaghi is fast-growing, wood density is relatively high compared to other fast-growing species. Cadaghi trees can produce more carbon in short period. Because of the high wood density, cadaghi may have wider applications. Cadaghi also had some medicinal value (Adeniyi et al., 2006) and was suitable for pulpwood (Guha et al., 1970). Therefore, its potential applications and markets should be explored so that the growers could be compensated for the land occupied by the windbreak either from wood products or carbon markets.

- People usually are reluctant to introduce non-native species because of invasiveness issues. Cadaghi's potential for invading natural areas is still unknown. Seeds were dispersed by gravity and bees (Wallace and Trueman, 1995; Wallace et al., 2008) and regeneration has been observed in the understory of the current windbreaks. Its invasive potential should therefore be studied.

APPENDIX A
EXTRA FIGURES FROM CHAPTER THREE

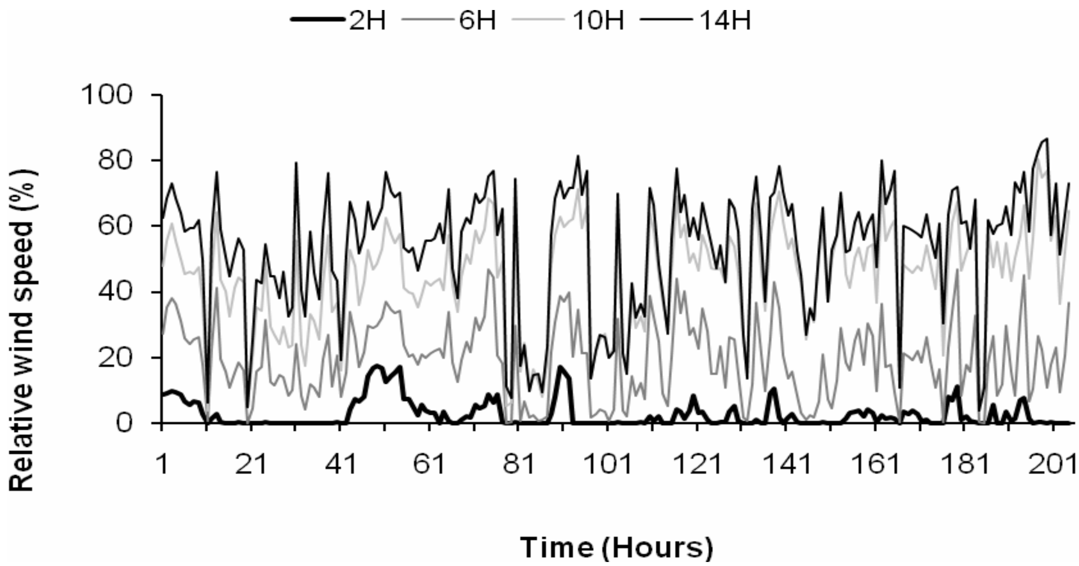

Figure A-1. Relative wind speed at different distances on the south side of the eastern redcedar windbreak at the SWFREC when the wind direction was between 45 and 135 degrees (90±45 degrees) to the windbreak and open wind speed was >1 m/s.

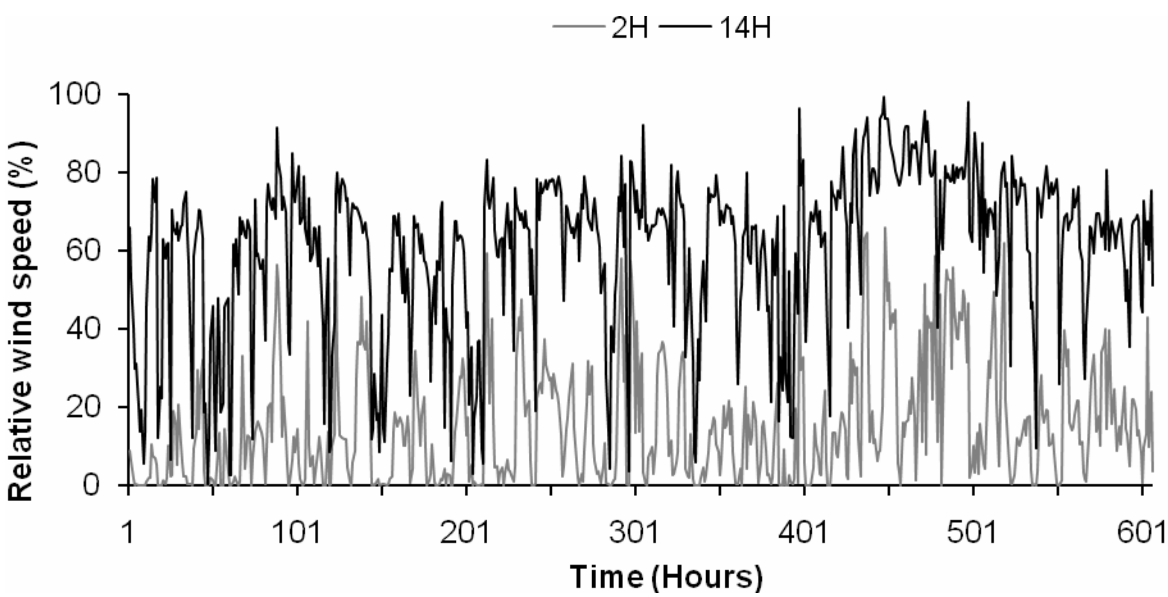

Figure A-2. Relative wind speed at 2H and 14H on the south side of the eastern redcedar windbreak at the SWFREC when the wind direction was less than 45 and greater than 135 degrees to the windbreak and open wind speed was >1 m/s.

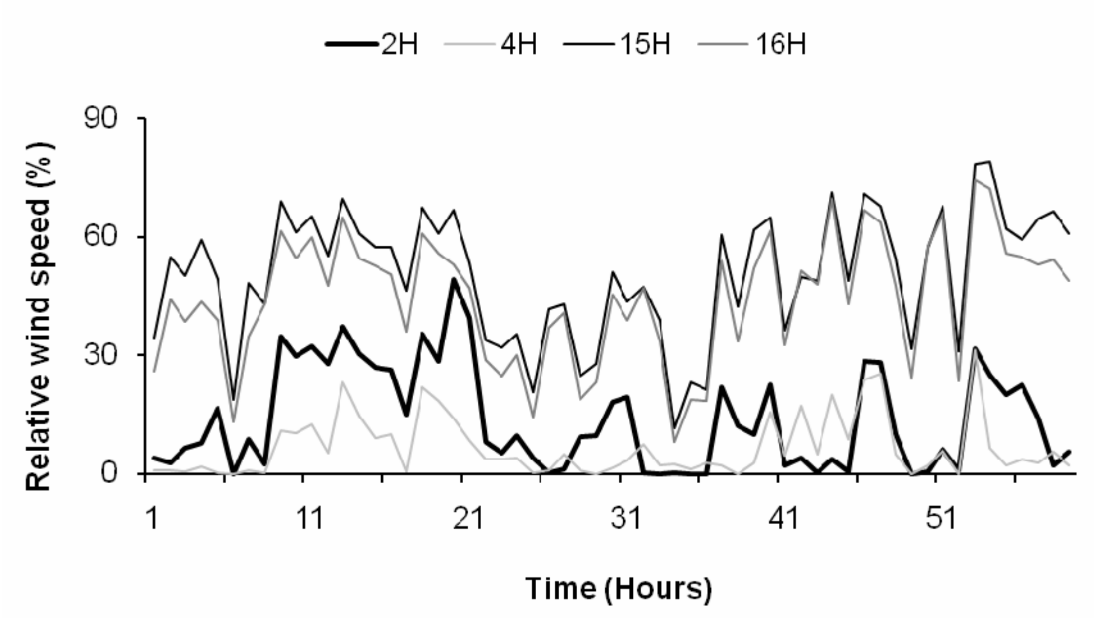

Figure A-3. Relative wind speed on the south side of cadaghi windbreak WB1 at C&B Farms at different distances when wind direction was nearly perpendicular (90±15 degrees) to the windbreak and open wind speed was >2 m/s.

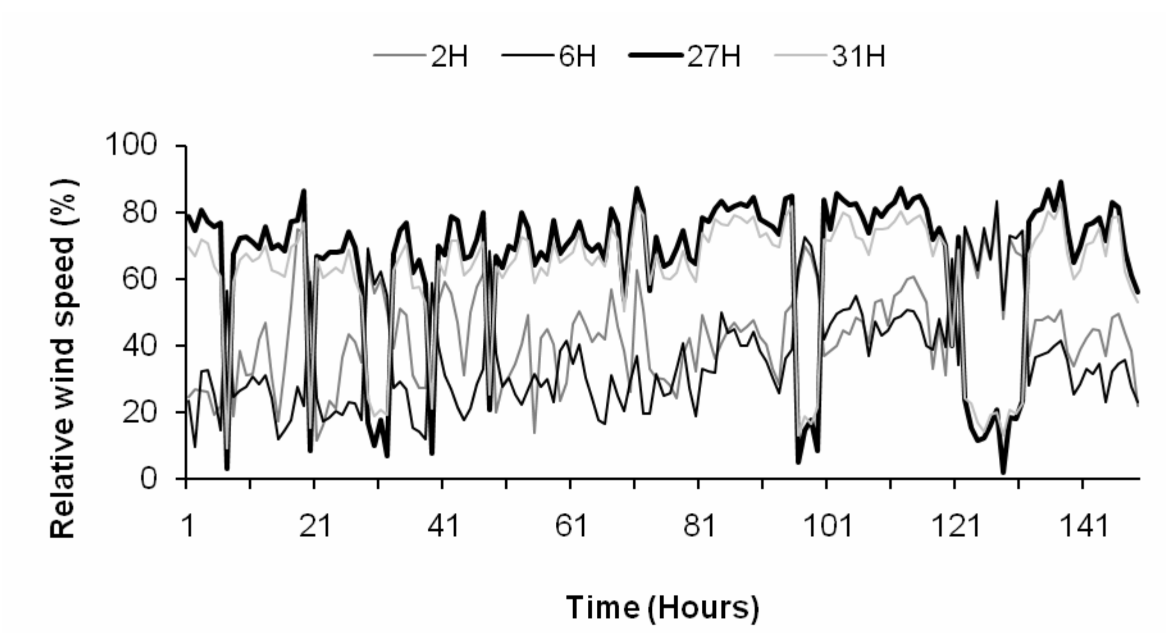

Figure A-4. Relative wind speed on the north side of cadaghi windbreak WB2 at C&B Farms at different distances when wind direction was between 60 and 120 degrees (90±30 degrees) to the windbreak and when open wind speed was >3 m/s.

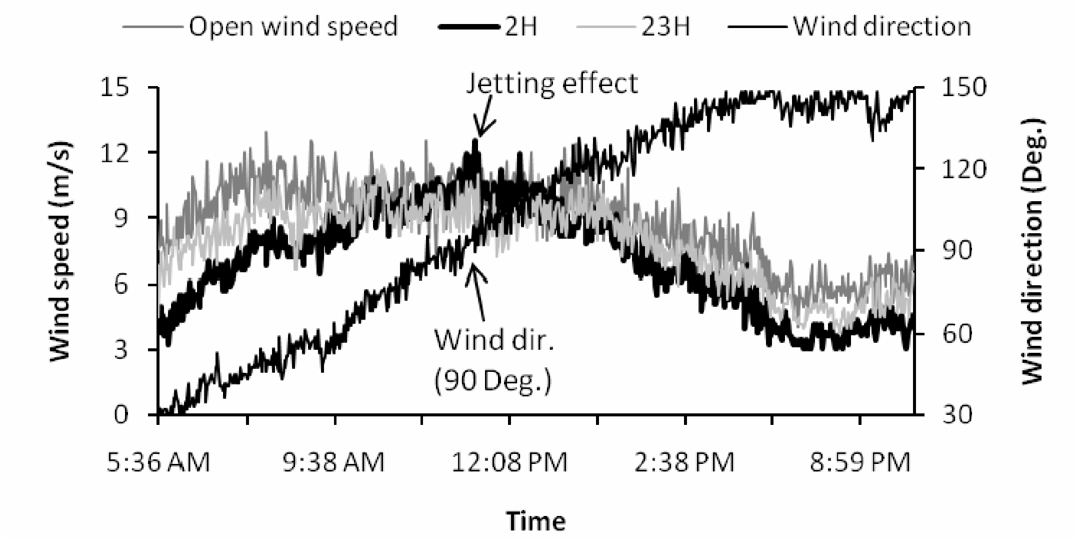

Figure A-5. Wind speed on the north side of cadaghi windbreak WB2 at C&B Farms during tropical storm Fay on August 19, 2008 when the wind direction was between 30 and 150 degrees (90±60 degrees) to the windbreak.

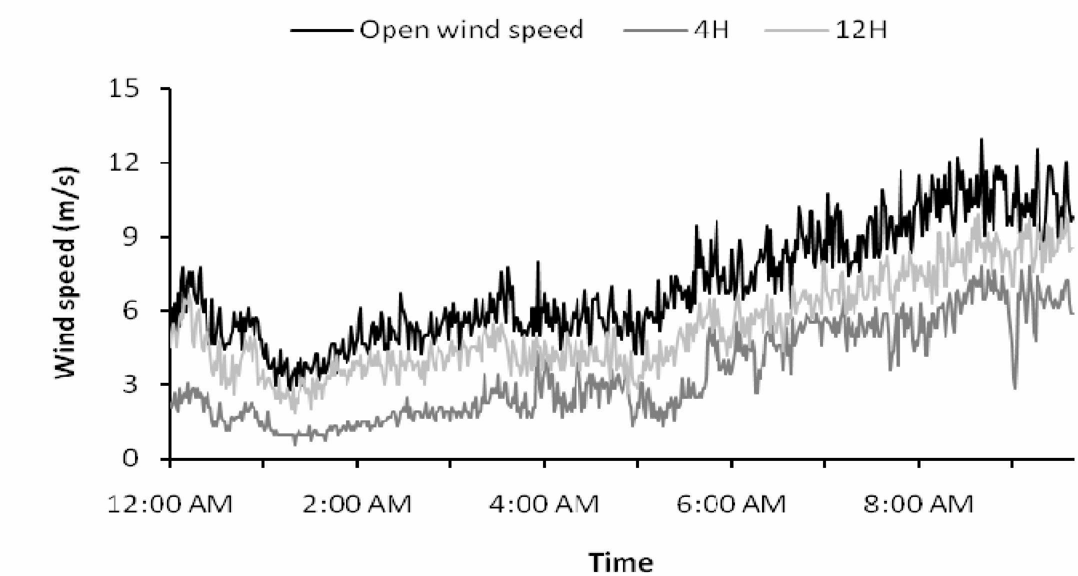

Figure A-6. Wind speed on the west side of cadaghi windbreak WB3 at C&B Farms during tropical storm Fay on August 19, 2008 when the wind direction was between 30 and 150 degrees (90±60 degrees) to the windbreak.

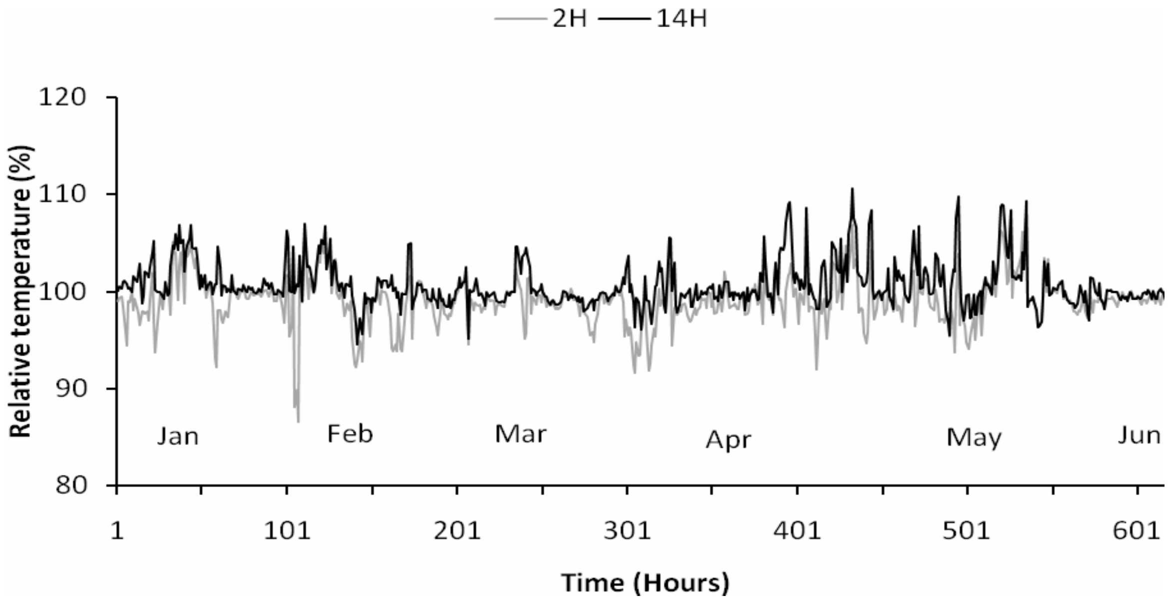

Figure A-7. Nighttime temperature at 2H and 14H on the south side of the redcedar windbreak at the SWFREC during normal weather conditions when the wind direction was between 0 and 180 degrees to the windbreak. Month above the time axis indicates the beginning of the month.

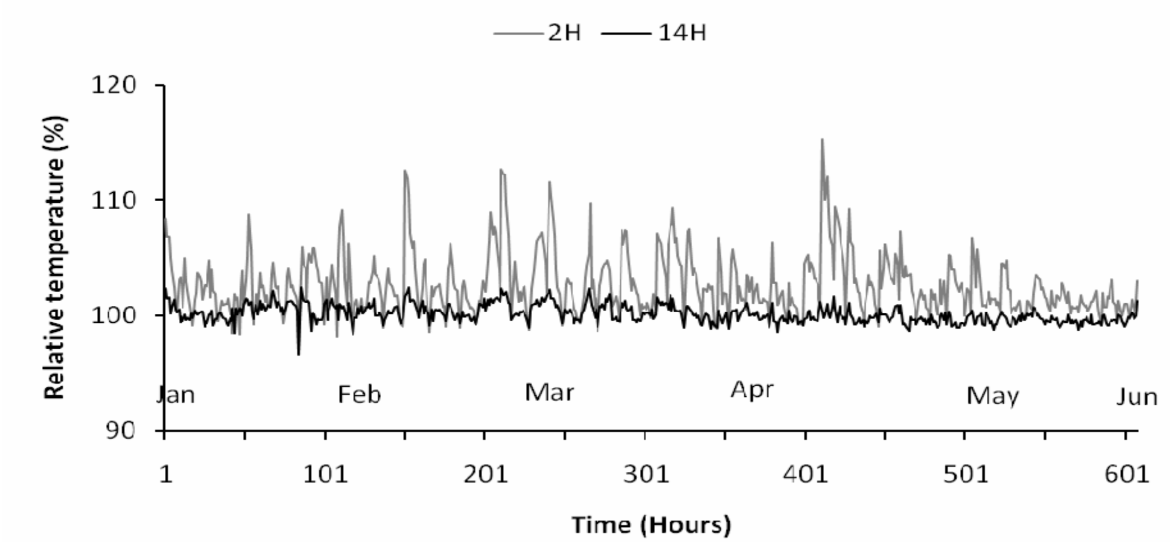

Figure A-8. Daytime temperature at 2H and 14H on the south side of the redcedar windbreak at the SWFREC during normal weather conditions when the wind direction was between 0 and 180 degrees to the windbreak. Month above the time axis indicates the beginning of the month

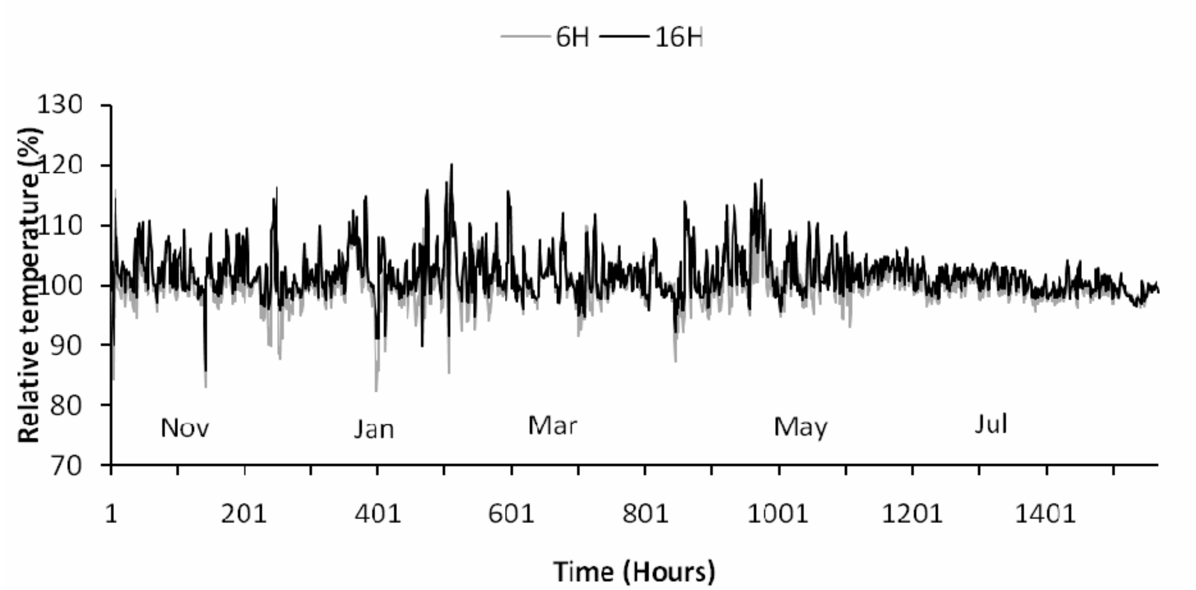

Figure A-9. Nighttime temperature at 2H and 16H on the south side of cadaghi windbreak WB1 at C&B Farms during normal weather conditions when the wind direction was between 0 and 180 degrees to the windbreak. Month above the time axis indicates the beginning of the month.

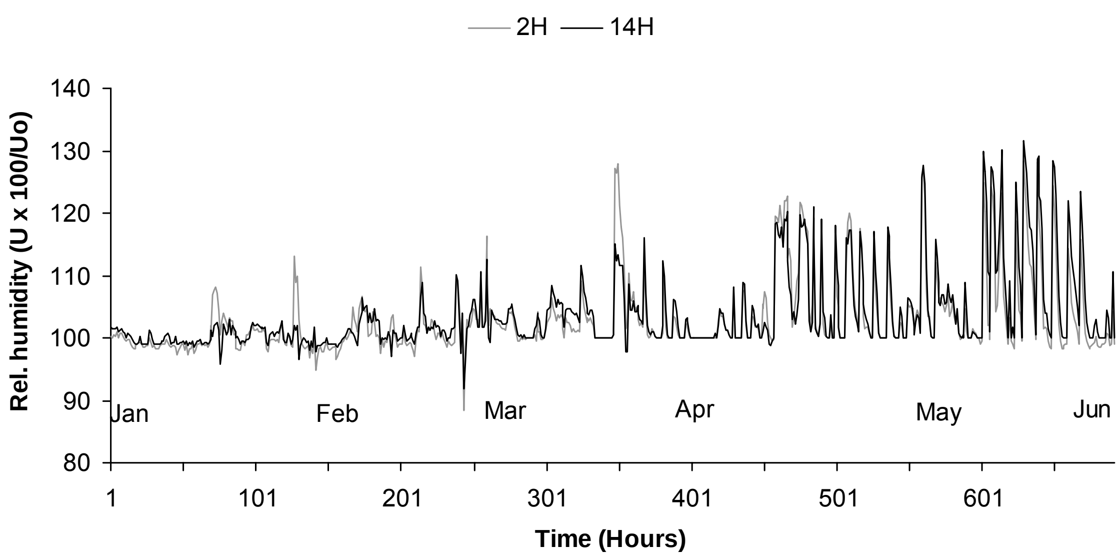

Figure A-10. Nighttime RH at 2H and 14H on the south side of eastern redcedar windbreak at the SWFREC. U is the RH on the leeside of the windbreak and Uo at the control station. Month above the time axis indicates the beginning of the month.

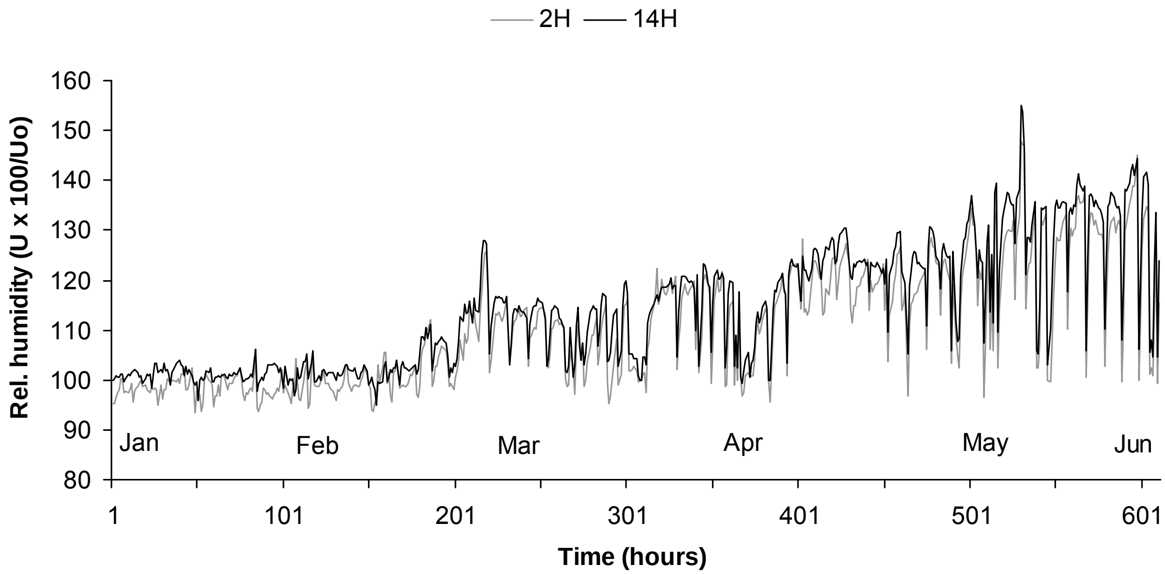

Figure A-11. Daytime RH at 2H and 14H on the south side of eastern redcedar windbreak at the SWFREC. U is the RH on the leeside of the windbreak and Uo at the control station. Month above the time axis indicates the beginning of the month

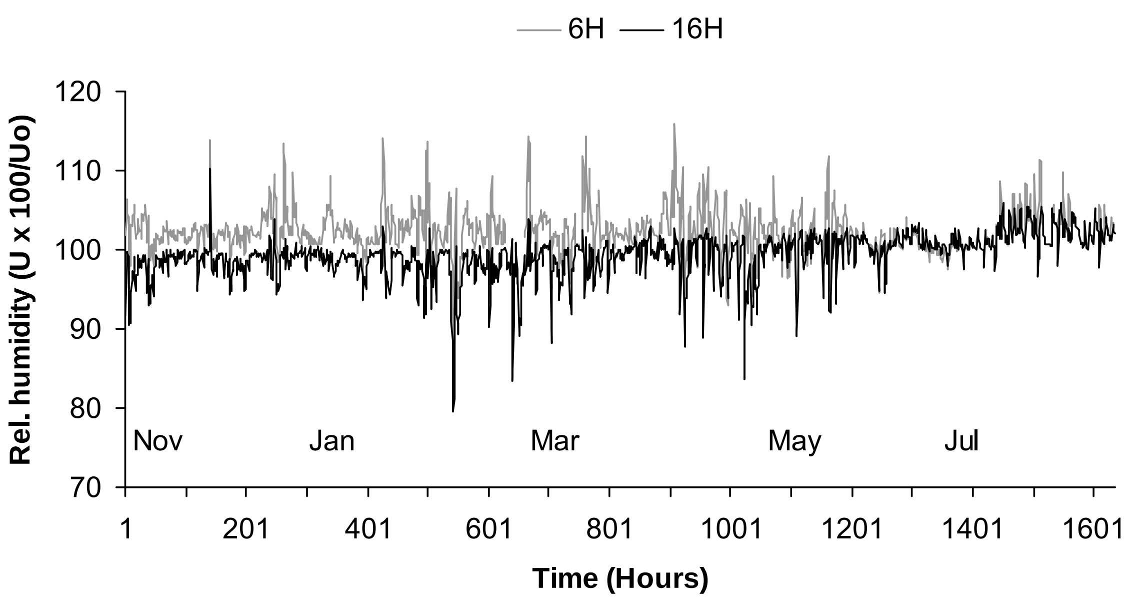

Figure A-12. Nighttime RH at 6H and 16H on the south side of cadaghi windbreak WB1 at C&B Farms when the wind direction was north. U is the RH on the leeside of the windbreak and Uo at the control station. Month above the time axis indicates the beginning of the month.

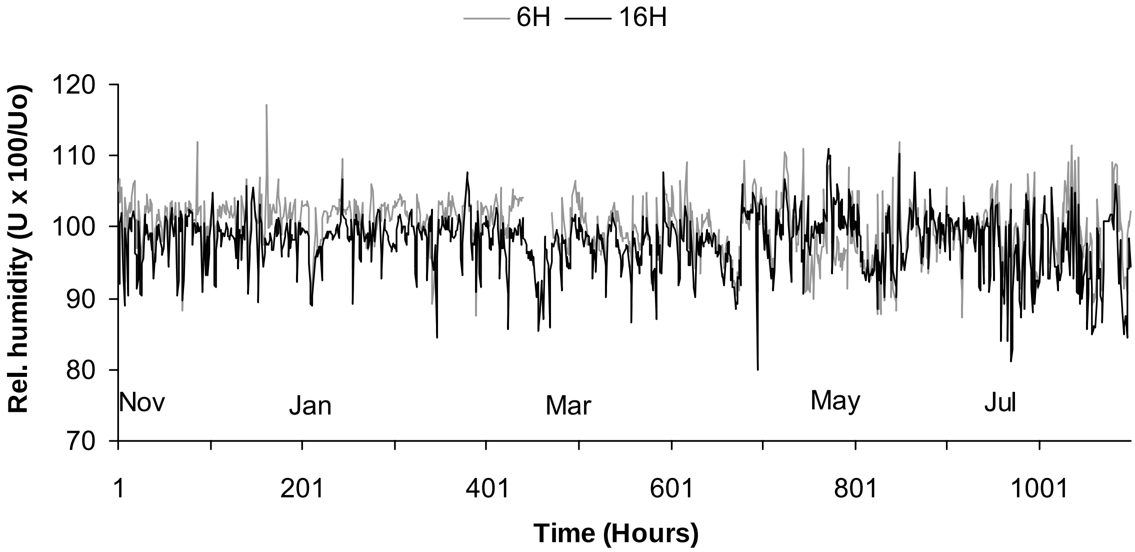

Figure A-13. Daytime RH at 6H and 16H on the south side of cadaghi windbreak WB1 at C&B Farms when the wind direction was north. U is the RH on the leeside of the windbreak and Uo at the control station. Month above the time axis indicates the beginning of the month.

APPENDIX B
PICTURES

Figure B-1. 20-year-old eastern redcedar windbreak at SWFREC/UF.

Figure B-2. 20-year-old cadaghi windbreak WB1 at C&B Farms.

Figure B-3. 8-year-old cadaghi windbreak WB2 at C&B Farms.

Figure B-4. 6-year-old cadaghi windbreak WB3 at C&B Farms.

Figure B-5. 2-year-old cadaghi windbreak WB5 at C&B Farms.

Figure B-6. Automated weather station used to measure wind speed, temperature and relative humidity (RH).

Figure B-7. Root sampling at C&B Farms.

Figure B-8. Biomass sampling at C&B Farms.

Figure B-9. Eggplant at about 3H from cadaghi windbreak WB1 with relatively more frost damage at C&B Farms in January 2009.

Figure B-10. Eggplant at about 16H from cadaghi windbreak WB1 with less frost damage at C&B Farms in January 2009.

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BIOGRAPHICAL SKETCH

Bijay Tamang was born in Kathmandu, the capital of Nepal, in 1974. He earned his bachelor's degree in biology in 1995 and master's degree in zoology (specialization in ecology) in 1998 from Tribhuvan University, Kathmandu. After his graduation, he studied population distribution of two endangered birds, Bengal Florican (*Houbaropsis bengalensis*) and Lesser Florican (*Sypheotides indica*), in the protected areas of lowland Nepal with his teammates from 1998-2001. He also worked on a vulture project in 2002-2003. He was an active member of Bird Conservation Nepal since the late 90s and now is a life member. He actively promoted bird conservation, and conducted several educational and awareness programs. He also worked with the International Bible Society in Nepal from 1996-2003. He began a Master of Science program at the University of Florida (UF) in the School of Forest Resources and Conservation in 2003, assessed the performance of fast-growing trees for cogongrass (*Imperata cylindrica*) suppression and colonization of understory plant in old phosphate mine lands in central Florida, and graduated in 2005. He then joined the doctorate program studying windbreaks of fast-growing trees in Florida. During his time at UF, he assisted in several phytoremediation, ecological restoration, and biomass/bioenergy projects involving fast-growing trees.