The snow in the willows: assessing the use of shrub-willows (*Salix* spp.) for living snow fences in Minnesota, USA

A Thesis
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

Eric J. Ogdahl

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Diomy S. Zamora

December 2015

ACKNOWLEDGEMENTS

This thesis would not be possible without the guidance and support of my professors, colleagues, friends and family. First and foremost, I thank my advisor, Diomy Zamora, for giving me the opportunity to work on this project and his support throughout my master's work. His open-door policy made progressing on this project, although challenging and new, efficient and relatively stress-free. Moreover, his sense of humor, flexibility, and homemade snacks made this project enjoyable. I am especially grateful to him for providing me with an insider's introduction to the exciting and growing world of agroforestry. Through joining him on farm tours, field trips, and workshops, I've been fortunate to meet farmers and landowners passionate about conservation, which provides inspiration and hope in a time of climate change and other global change issues.

I thank my committee members Gregg Johnson and Dean Current for helping lay the foundation for this project and providing useful feedback on drafts of this thesis. Gregg was especially helpful in helping me understand things we were observing in the field, why herbicide applications weren't working, and that the willows *would be okay*.

I am grateful to Extension Educator Gary Wyatt, a CO-PI on this project. Gary spent perhaps the most time with me out in the field and was always willing to lend a hand, no matter how low the windchill got to be. Gary has played a big role in the outreach and research efforts regarding living snow fences, which have been invaluable to this project. In addition, his creativity in and enthusiasm for promoting agroforestry and rural conservation practices are inspiring.

Other project members I am grateful for are David Smith and MnDOT forester and living snow fence champion Dan Gullickson. David provided many useful comments on initial drafts for this project and posed numerous useful suggestions and questions throughout this research. Dan brought forth extensive knowledge of and experience with living snow fences, which helped tremendously in improving my understanding of living snow fences.

Thanks goes to the funding sources for this research. This project was supported by a grant from the Minnesota Local Road Research Board and the Minnesota Department of Transportation (MnDOT Contract 99008) and housed at the University of Minnesota's Center for Transportation Studies.

A big thanks goes to all who donned the yellow highway vests with me in the field. I thank fellow students Alex Mehne, Josh Gamble, and Jenny Haug, especially for braving the often thankless, cold and windy weather we had during field measurements. A great thanks goes to Benjamin Katorosz for helping in the field throughout the project. He always brought a good sense of humor to the job and made the drive to and from the field more enjoyable. I also thank the local 4-H and Boy Scout groups who helped out planting the experiments and weeding them. Thanks also goes to the great staff at the

Southern Research and Outreach Center—especially Tom Hoverstad and Paul Adams—who helped during various stages of the project, especially with machinery. I also owe thanks to Don Baker from MnDOT’s Waseca Truck Station for helping with site preparation and supporting living snow fence efforts.

I acknowledge all of the researchers and experts who have contributed to this project along the way. Thanks goes to Justin Heavey and Tim Volk of the Willow Program (Syracuse University New York-College of Environmental Science and Forestry) for their helpful suggestions and information regarding willow and porosity measurements. I also thank Martha Shulski of University of Nebraska, School of Natural Resources, for providing pertinent information regarding living snow fence measurements. Thanks also to Rafiq Islam, Ohio State University, for analyzing our soil samples. Felipe Acosta (Statistical Consulting Service, University of Minnesota) is also appreciated for providing helpful assistance and suggestions during the data analysis.

I thank the people who encouraged me in my research interests during my undergraduate career, especially Elizabeth Borer, Jim and Sehoya Cotner, Missy Rudeen, and Eric Lind.

I’m thankful for the people I’ve gotten to know, work with and learn from in the past few years who have been sources of wisdom and inspiration to me: Lawson, Lynden, Chel, and Ron.

Lastly, I’m thankful for my family, nuclear and extended, for their constant support and love, warm get-togethers, and shared enjoyment of the outdoors. I thank my furry sister Lily, for warm welcomes and walks around the pond. I’m grateful to Claudia for her support, encouragement, shared goofiness, and companionship. And most of all, I thank my parents, Brian and Char, for their unwavering support, patience, guidance, and love. For all the experiences you’ve given me and for showing me the love of the land, thank you.

DEDICATION

This thesis is dedicated to my parents.

ABSTRACT

Blowing and drifting snow adversely affect winter driving conditions and road infrastructure in Minnesota, often requiring removal methods costly to the state and environment. Living snow fences (LSFs)—rows of trees, shrubs, or grasses installed on fields upwind of roadways—are economically viable solutions for controlling drifting snow in agricultural areas and can provide a range of environmental benefits, such as carbon sequestration and wildlife habitat. Despite incentives and financial assistance by state and federal agencies, farmer adoption of LSFs is low, in part due to concerns about removing cropland from production. Shrub-willows (*Salix* spp.) have been proposed as a LSF species to meet landowner needs, given their potential to reach effective snow fence heights and densities soon after planting and provide a marketable biomass product. As part of evaluating the use of willow LSFs for multiple benefits in Minnesota, this thesis sought to 1) assess the establishment and snow trapping ability of three willow varieties in two- and four-row planting arrangements in a LSF in south-central Minnesota, and 2) compare the establishment and growth of both native and hybrid shrub-willow varieties and species to species traditionally used in Minnesota LSFs (i.e., Gray dogwood and American cranberrybush).

In the first study, willows had an average survival rate of 89% and average growth of 1 meter after two growing seasons. Over the 2014-15 winter, no differences were found among willow varieties in their ability to trap snow; however, four-row arrangements caught more snow than two-row arrangements. Blowing snow models indicated that two-and four-row arrangements should be able to trap all of the mean annual snow transport for the study region after three and four growing seasons, respectively. In the second study, all species showed good establishment, and all willows exceeded the growth of traditional LSF species after the second growing season. Additionally, a native willow (*S. petiolaris*) had similar growth to the top-growing hybrid willow varieties, suggesting it may provide a suitable local source for future LSFs. Overall, these results suggest that willows may provide effective LSFs earlier than traditional LSF species and add to the LSF design practices for transportation agencies, natural resource managers, and landowners.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Living snow fences (LSFs) are a cost-effective windbreak practice designed to mitigate blowing and drifting snow problems along transportation routes. Along with snow control, they provide environmental benefits such as wildlife habitat and carbon sequestration. Despite incentives and financial assistance by state and federal agencies for LSF establishment, landowner adoption of LSFs is low due to concerns about removing cropland from production and maintaining trees and shrubs. Shrub-willows (*Salix* spp.) have been proposed as a LSF species to meet landowner needs, as they are easily established, have potential to reach effective LSF heights and densities two to three years after establishment, and may provide a marketable biomass product. However, information regarding their establishment and snow storage capacity in LSF settings is limited. Furthermore, little is known about how shrub-willow establishment and growth compares to that of traditional LSF shrubs, as well as whether hybrid willow varieties are more suitable LSF candidates than native shrub-willow species. Therefore, studies were designed to 1) investigate establishment and potential snow storage capacity of three shrub-willow varieties in two LSF planting arrangements (two and four rows), and 2) compare the establishment and growth of hybrid willow varieties to that of a native shrub-willow species, as well as native shrubs traditionally used in LSFs in Minnesota.

CHAPTER 1: ESTABLISHMENT AND POTENTIAL SNOW STORAGE CAPACITY OF WILLOW (*SALIX* SPP.) LIVING SNOW FENCES IN SOUTH-CENTRAL MINNESOTA, USA

1.1 Introduction

Blowing and drifting snow adversely affect winter driving conditions and road infrastructure in cold-weather regions of the world, especially in areas dominated by annual crop production. These areas can create large expanses of open ground in the winter, whereby wind can relocate fallen snow onto adjacent transportation routes. In the United States, the costs associated with snow and ice removal and infrastructure damage are estimated to exceed US$7 billion per year (Isebrands et al. 2014). Not included in these costs are the injuries and accidents associated with blowing snow, as well as the adverse and indirect environmental effects of snow removal, such as runoff from road salt application (Fay and Shi 2012).

Living snow fences (LSFs)—windbreaks planted to intercept blowing snow—are a potentially cost-effective agroforestry solution to controlling blowing snow and ice on roadways (Shaw 1988; Daigneault and Betters 2000; USDA 2011; Tabler 2003). LSFs work by creating wind turbulence around their linear barrier upwind of a roadway, causing blowing snow particles to deposit around the fence rather than onto roads. Many of the trapped snow particles are deposited downwind of the LSF, requiring a setback distance between the LSF and roadway (Tabler 2003). By reducing the need for snow removal, LSFs, along with structural snow fences (SSFs) (e.g., wooden or metal snow fences), have been shown to provide government agencies with benefit-cost ratios of 2:1

to 36:1 (Gullickson et al. 1999; Daigneault and Betters 2001; Tabler 2003) and reduce accident rates by 75% (Tabler and Meena 2006). While LSFs and SSFs provide similar snow capture benefits, LSFs can require less annual maintenance than SSFs and exceed the functional lifetime and benefit-cost ratios of SSFs (Daigneault and Betters 2001; Isebrands et al. 2014). For example, Daigneault and Betters (2001) estimated a LSF could provide a benefit-cost ratio of 5.69, whereas two designs of SSFs had cost-benefit ratios of 2.41 and 2.03. Additionally, LSFs can provide a number of environmental benefits, such as wind erosion control (Brandle et al. 2009), wildlife habitat, and aesthetic enhancement along transportation routes (Shaw 1988).

In many cases, however, the limited widths of rights-of-way along roadways necessitate the placement of LSFs on privately owned land (Isebrands et al. 2014). This has led to a low adoption of LSFs, despite their numerous benefits. In Minnesota, USA, for example, approximately 1930 km of state roadways have severe blowing snow problems, but only 30 km have been addressed through landowner adoption of LSFs (Wyatt et al. 2012). Landowners have cited multiple barriers to LSF adoption, including removing cropland from production, hassle and time spent installing LSFs, and risk of plant mortality (Wyatt et al. 2012). Therefore, to improve LSF adoption, it is necessary to evaluate plants that are easily established and have potential to provide landowners with a marketable product.

Shrub-willows (*Salix* spp.) have been developed as a short-rotation woody crop (SRWC) (Volk et al. 2006) and proposed as a suitable LSF candidate (Kuzovkina and Volk 2009).

They are easily planted with dormant stem cuttings, have fast growth rates, produce dense shrubs with multiple stems, are adaptable to an array of site and climatic conditions (Volk et al. 2004), offer a marketable product as a biomass crop (Buchholz and Volk 2010), and offer numerous ecosystem services, such as pollinator and other wildlife habitat (Keoleian and Volk 2005; Rowe et al. 2011; Haβ et al. 2012) and carbon sequestration (Zan et al. 2001; Grogan and Matthews 2002). Additionally, shrub-willows have potential to achieve key growth parameters for controlling blowing snow sooner than species traditionally used in LSFs. For example, Heavey and Volk (2014) assessed a chronoseqence of shrub-willow LSFs in New York State, and found they had potential to prevent blowing snow on roadways as soon as three years after planting. This contrasts with other species typically used in LSFs, such as spruce (*Picea spp.*) or juniper (*Juniperus spp.*), which can require 5 to 20 years before functioning as effective LSFs (Sturges 1983; Powell et al. 1992; Tabler 2003). Many traditional LSF species also require multiple widely spaced rows for effective snow capture, whereas high-density shrub-willow LSF plantings may provide the same control in narrower arrangements (Isebrands et al. 2014). Aside from Heavey and Volk (2014) and Isebrands et al. (2014), however, little has been done to assess the use of shrub-willows for LSFs. In order to employ shrub-willow LSFs on the landscape, more work is necessary to determine appropriate variety selection and planting designs, as well as assess their growth parameters in relation to trapping blowing snow.

The amount of snow caught by a LSF is primarily influenced by its height and porosity (i.e., the amount of open space within a vegetative barrier) (Tabler 2003). As a LSF grows over time, its height increases and porosity decreases, allowing it to trap more snow in each successive year (Heavey and Volk 2014). This study sought to evaluate establishment and growth parameters as they relate to snow storage capacity in LSFs of three hybrid shrub-willow varieties and in planting arrangements of two and four rows. Using models developed by Tabler (2003), as well as field measurements, this study sought to determine whether LSFs were able to trap all of the blowing snow transported at the project site and assess whether and how varieties and planting arrangements affected snow storage capacity. Two hypotheses were tested in this study: 1) the ability of willows to trap snow is the same regardless of variety and 2) four-row planting arrangements trap more snow than two-row arrangements based on lower overall porosities.

1.2 Materials and Methods

1.2.1 Site description and experimental design

The study was established in May 2013 on the Minnesota Department of Transportation (MnDOT) right-of-way on the north side of U.S. Highway 14 (44°03’32” N; 93°31’12”) in Waseca, Minnesota, USA, which is adjacent to the University of Minnesota’s Southern Research and Outreach Center (SROC). The north side of the highway was selected in part due to strong west-northwest winds during winter months (Shulski and Seeley 2004), leading to blowing and drifting snow on the highway. Waseca’s climate is characterized by warm summers and cold winters, with a 30-year (1981-2010) normal (average) temperature and precipitation of 7.1°C and 91 cm, respectively (NCDC 2015). Soils at the study site were formed in loamy, calcareous till and are very deep and well-drained to very poorly drained. Soils consist of Clarion (Fine-loamy, mixed, superactive, mesic Typic Hapludolls), Cordova (Fine-loamy, mixed, superactive, mesic Typic Argiaquolls), Glencoe (Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls), and Nicollet (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls) soil series. The study site ranges in slopes between 0 and 5%. Soil characteristics for the site are presented in Table 1.1. Prior to establishment, the study site consisted primarily of weeds, such as Canada thistle (*Cirsium arvense* (L.) Scop.) and common ragweed (*Ambrosia artemisiifolia* L.), and annual grasses (e.g., *Setaria* spp.). In May, 2013, the site was sprayed with 1.3 kg ha^{-1} a.i. glyphosate [N-(phosphonomethyl)glycine] to control annual and perennial weeds. The site was rototilled to a soil depth of about 10 cm in June 2013, approximately one week before planting.

The study site was established in a factorial randomized complete block design with willow varieties 1) *Salix purpurea* ‘Fish Creek’, 2) *S. purpurea* × *S. miyabeana* ‘Oneonta’, and 3) *S. caprea* × *S. cinerea* ‘S365’. These varieties were established in planting arrangements of two and four rows replicated four times (Figure 1.1). These willow varieties were selected based on their fast establishment and ability to produce a high number of stems in previous willow trials and experiments in Minnesota (Gamble et al. 2014; Zamora et al. 2014). Willow cuttings were obtained from Double A. Willow Inc., in Fredonia, New York, USA. The site was planted manually with 20-cm-long dormant willow stem cuttings to a depth of about 14 cm in plots 18.3 m long and 2.3 m wide. Following willow LSF designs in New York State (Heavey 2013), plants within rows were spaced 60 cm apart and plants between rows were spaced 76 cm resulting in 31 plants row^{-1}. All plots were aligned along their northern-most row to create a continuous upwind snow fence edge. Additionally, between-plot spacing was the same as within-row spacing to prevent any gap effects on snow drifting (Tabler 2003). While willows are typically coppiced in the fall after planting to promote multiple stem sprouting and growth, the willows in this study were not coppiced until early April 2014, prior to bud sprouting, such that first-year stems could provide an early barrier to trap blowing snow.

Shortly after planting, the study site was managed for post-emergent weeds. In 2013, plots were sprayed with 0.3 kg ha^{-1} a.i. clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) and 0.2 kg ha^{-1} a.i. sethoxydim {2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one}. Additionally, plots were cultivated in July 2013, followed by manual weed control throughout the remainder of the growing season.

1.2.2 Plant data collection

To evaluate shrub establishment, survival was assessed at approximately one month after planting and one growing season post-coppice. In the first assessment, all plants in the experiment were surveyed for visible growth and restocked accordingly. In the second assessment, a sample area (4.2 m^2) was demarcated in the center of each row following protocols developed by the State University of New York (SUNY) willow breeding program (Cameron et al. 2008) to assess willow performance and growth. Ten plants in the demarcated area in each row of each plot were assessed after one growing season post-coppice.

To assess willow growth in relation to snow storage capacity, heights were measured in the fall of 2014 in the demarcated sampling area. For all plants in the sample area, the height of the tallest stem was recorded to the nearest centimeter, following SUNY willow measurement protocols (Cameron et al. 2008). Porosity was measured with the chroma-key technique (adopted from Heavey and Volk 2014) in the early winter of 2014, after leaf drop. Measurements were taken at 4 equidistantly spaced points in each plot, starting at approximately 3.7 m from the end of each plot. At each point, a 1 m wide by 3 m tall red backdrop was placed behind the fence and photographed with a digital camera (Figure 1.2). Photographs were taken at a consistent height above the ground at approximately 3.3 m from the front of each fence point to capture the entire backdrop. Photographs were then processed in Adobe Photoshop by removing the area outside of the backdrop, leaving only the backdrop and the vegetation in front of it, and cropping the photo to the approximate height of each sample point. To obtain porosity values, the number of backdrop pixels were counted and divided by the total number of pixels in the entire cropped area and multiplied by 100.

1.2.3 Modeled snow storage capacity

The methodology for determining a LSF’s effectiveness was developed by Tabler (2003) and has been applied to multiple studies (e.g., Shulski and Seeley 2004; Blanken 2009; Heavey and Volk 2014; see Appendix A). Tabler (2003) developed models such that the snow storage capacity (Q_c) of a LSF (i.e., the amount of snow a LSF can store per linear meter) can be compared to the mean annual snow transport (Q), defined as the mean quantity of blowing snow per linear meter, occurring at the location of a LSF. With both Q_c and Q in units of metric tons of water equivalent per meter (t m^{-1}), the ratio of Q_c:Q can determine a LSF's snow trapping efficiency (Heavey and Volk 2014). Q_c is influenced by a LSF's height and porosity and determined as described by Heavey and Volk (2014). Q is delimited by the snow accumulation season (SAS), defined as the number of consecutive days during the winter for which the average temperature is below 0^oC, and is determined as described by Tabler (2003) (see Appendix A). Over the SAS, Q is influenced by climatological and site characteristics of a LSF's location. These include the fetch distance (F) of the site; the relocation coefficient (θ), or fraction of snowfall relocated by the wind; and the snowfall water equivalent (S_{we}) (Tabler 2003; Heavey and Volk 2014).

To model Q_c, height and porosity measurements were averaged by treatment and calculated following previous assessments (Tabler 2003; Heavey and Volk 2014).

In determining Q, the SAS was determined using thirty-year monthly normal temperatures (1981-2010) for SROC, obtained from the National Climatic Data Center (NCDC 2015), and calculated as described by Tabler (2003) (Appendix A).

To orient F measurements at the study site, the prevailing direction of snow transport was determined from a combination of wind direction and speed data, as well as field observations. Wind direction and speed data were obtained for 5 SAS, beginning 16 Nov

2010 and ending 17 Mar 2015, from the Waseca Municipal Airport (44 ^{o}4’24” N, 93^{o}33’11” W), approximately 3.1 km from the study site (Appendix A). The airport has an Automated Surface Observing System (ASOS), which utilizes standardized wind instrumentation mounted at a height of 10 m (Shulski and Seeley 2004). Five SAS were assumed to be an adequate representation on wind speed and direction based on previous assessments (Tabler 1997; Shulski and Seeley 2004). Data were summarized following previous studies (Tabler 1997; Shulski and Seeley 2004) to model the prevailing direction of snow transport (Appendix A). The estimated prevailing direction of snow transport was verified through field observations over the 2013-2014 and 2014-2015 SAS dates by measuring the direction of streamlined drift contours at the study site (Tabler 2003; Appendix A). This provides an average direction of drifting and thus the prevailing direction of snow transport for the area (Tabler 2003).

F was calculated in a GIS by orienting F length measurements for each plot in the study to the approximate prevailing snow transport direction. F measurements spanned from the center of each plot to the nearest wind obstruction, such as a homestead or road ditch. These measurements were then averaged to obtain a single F value for use in the Q model (Heavey and Volk 2014). Snowfall water equivalent (S_{we}) was determined by multiplying the mean snowfall over the SAS by the average snow water equivalent. The mean snowfall over the SAS was obtained from thirty-year monthly normals (1981-2010) for SROC (NCDC 2015) and the average snow water equivalent (0.113) was determined from a previous assessment of blowing snow characteristics in Minnesota (Shulski and Seeley 2001; Appendix A). A relocation coefficient (θ) of 0.4 was used based on previous assessments by Shulski and Seeley (2001; 2004). These blowing snow parameters were used to calculate Q (Tabler 2003; Heavey and Volk 2014). Q was then compared to the Q_c of each LSF treatment to determine each treatment's trapping efficiency (Heavey and Volk 2014).

1.2.4 Measured snow storage

Snow field measurements were taken over the 2014-2015 winter to assess snow storage around each willow variety and planting arrangement. In each plot, measurements were taken along a transect oriented to the prevailing west-northwest wind direction. A graduated polyvinyl chloride tube with a 5-cm diameter was used to measure snow drift heights at points spaced approximately 3 m apart, both upwind and downwind of the snow fences (adopted from Tabler 1980; Shulski and Seeley 2001). The transects spanned from 3 m upwind of the center of each plot to 6 m downwind of the plot's center, resulting in 4 depth measurements per plot. In assessing a LSF's snow storage capacity, snow measurements are typically taken at the end of the SAS (Shulski and Seeley 2001). This provides an estimation of the LSF's equilibrium drift, which is the cumulative cross-sectional area of a snow drift around a snow fence (Tabler 2003), once a snow fence has been filled to capacity (Shulski and Seeley 2001). In this study, above-freezing dates and rain events occurred shortly after the first snow events in November 2014, and continued to occur throughout the winter (Table 1.2). Due to this, measurements were attempted between snowfall events and predicted above-freezing dates. Measurements were collected for a total of three dates between Dec 2014 and Mar

2015. Snow storage was determined for each collection date by estimating the cross-sectional drift area using snow height measurements, following protocols developed by Tabler (1997) and Shulksi and Seeley (2001). To attain snow measurements on a mass basis, drift area was multiplied by an assumed snow density of 600 kg m^{-3}, based on previous snow fence assessments in southern Minnesota (Tabler 1997).

1.2.5 Statistical analyses

Linear mixed effects models were used to examine the effects of willow variety and planting arrangement on survival, height, porosity, and measured snow storage. For each parameter, willow variety and planting arrangement were included as fixed effects and tested for significance and interaction via Wald's Chi-squared test. In the survival and height models, the planting arrangement covariate included both the number of rows in each plot (i.e., two or four rows) and the row position of the measured plants within each row arrangement (i.e., for two rows, north edge row or north middle row, and for four rows, north edge row, north middle row, south middle row, or south edge row). To account for the nested structure in both plant and measured snow transport data, replicate and plot number were included as random effects (Pinheiro and Bates 2000). Also, for measured snow transport, measurement date was considered a repeated measure and thus included as a random effect. Where main effects were significant at $\alpha = 0.05$, Tukey's honestly significant difference (HSD) for multiple comparisons was used to test for differences among means at $\alpha = 0.05$. Linear regression was used to determine the relationship between porosity and number of double rows in our study. The natural log was used to transform porosity data, as I expected a negative exponential relationship between porosity and the number of rows. To predict storage capacity (Q_c) in future years, I applied this relationship to models developed by Heavey and Volk (2014) relating shrub-willow LSF porosity and height to LSF age. All statistical analyses were performed in R (v. 3.0.2; R Foundation for Statistical Computing, Vienna, Austria).

1.3 Results

1.3.1 Establishment and growth

Willows in the LSF had an average survival rate of 89% across varieties after one growing season post-coppice. The overall survival rates for Fish Creek, Oneonta, and S365 were 89%, 81%, and 96%, respectively. No interaction was found between variety and row arrangements; however, variety had a significant effect on survival ($P = 0.015$). Tukey's comparison indicated that Oneonta had a significantly lower survival rate than S365 ($P = 0.011$), while Fish Creek's survival was not significantly different than Oneonta or S365.

The mean height for all LSF willows after one growing season post-coppice was 107.5 ± 1.5 cm. Willow varieties Fish Creek, Oneonta, and S365 had average heights of 123.7 ± 2.5 cm, 108.4 ± 2.8 cm, and 91.7 ± 1.9 cm, respectively. Willow variety ($P = 0.005$) and planting arrangement ($P<0.001$) significantly affected willow height; however, no interaction was observed between them. Among varieties, Fish Creek had a significantly greater height than S365 by approximately 32 cm ($P = 0.008$), while no significant differences were found between Fish Creek and Oneonta and Oneonta and S365. Among planting arrangement effects, no significant difference was found between willow heights in two- and four-row arrangements; however, within planting arrangements, height differences were found among the position of rows. In general, edge rows were shorter than inner rows (Figure 1.3). Specifically, in two-row arrangements, willows in the north row were, on average, shorter than those in the inner row ("mid north") but were not significantly different at $\alpha = 0.05$. A similar observation was made within the four-row arrangements. The heights of willows in the north and south rows were shorter than the inner rows ("mid north" and "mid south") but not significantly different at $\alpha = 0.05$.

After one growing season post-coppice, willow LSFs had a mean porosity of 83.6 ± 0.7% across varieties and planting arrangements (Figure 1.4). Porosity was not significantly different among willow varieties but was significantly different between planting arrangements ($P<0.001$). The average porosity values for two- and four-row arrangements were 87.3 ± 0.7 % and 79.9 ± 1.1 %, respectively.

The regression analysis between natural log porosity and number of double rows yielded a modest but significant linear relationship ($B = -0.092$, $P<0.001$, $R^2 = 0.25$):

$$\text{LnPorosity} = -0.13736 - 0.092(n - 1) \qquad (1)$$

where LnPorosity is the natural log of porosity as a decimal and n is the number of double rows. This suggests that each additional double row has a porosity of 91%. Simplified, this yields the following relationship:

$$\text{Porosity} = 0.87 * 0.91^{(n-1)} \qquad (2)$$

1.3.2 Snow storage capacity

By incorporating height and porosity values, modeled Q_c varied from <1–9 t m^{-1} among willow variety and planting arrangements (Table 1.3). These were compared to Q at the study site, which was determined to be 39.9 t m^{-1} over a snow accumulation season of Nov 16 to Mar 17 and with a prevailing snow transport direction of west-northwest and an average fetch distance of 1330 ± 28.5 m. The ratios of $Q_c{:}Q$ for all of the willow varieties and planting arrangements were less than 1, meaning that none of the treatments had a Q_c sufficient to trap all of the predicted Q at the study site location (Table 1.3). However, using shrub-willow height and porosity models from Heavey and Volk (2014) and this study's relationship between rows and porosity (Equation 2), it was observed that modeled Q_c values of two-row willow LSFs could potentially exceed the local Q 4 years after planting by 113%, whereas those of four-row LSFs could exceed local snow transport 3 years after planting by 35% (Table 1.4).

From empirical snow storage measurements, I observed all willow LSFs were trapping snow throughout the snow accumulation season and that four-row planting arrangements tended to catch more snow than two-row planting arrangements (Table 1.5, Figure 1.4). Across observation dates, willow variety did not have a significant effect in predicting snow transport, but the effect of planting arrangement was significant (P<0.001). On average, four-row planting arrangements tended to capture 1.2 times the snow transport compared to two-row planting arrangements (Figure 1.4).

1.4 Discussion

Like all SRWC applications, high plant survival is a desirable factor in achieving effective LSFs as this can improve porosity and thus snow storage capacity. Willows in our study had acceptable survival. Although there is no defined survival rate threshold for effective LSFs, two-year (one growing season post-coppice) survival rates of all willow varieties in the study were above the 80% establishment threshold for productive SRWC stands (Bergkvist et al. 1996). Among willow varieties, Oneonta had the significantly lowest mean survival rate of 81%; however, this did not appear to affect measured snow storage at our site, given the lack of a willow variety effect. Studies documenting LSF survival rates are limited, but two previous studies found a wide range of survival rates for different coniferous, deciduous, and shrub species. Sturges (1983) found second-year survival rates of 20-94% for blue spruce (*Picea pungens* Engelm.), ponderosa pine (*Pinus ponderosa* P. & C. Lawson), white fir (*Abies concolor* (Gord. & Glend.) Lindl. Ex Hildebr.), Russian olive (*Elaeagnus angustifolia* L.), Siberian elm (*Ulmus pumila* L.), Siberian peashrub (*Caragana arborescens* Lam.), big basin sagebrush (*Artemisia tridentate* Nutt. subsp. *tridentata*), southernwood (*A. abrotanum* L.), and white rabbitbrush (*Ericameria nauseosa* (Pallas ex Pursh) G.L. Nesom & Baird) LSFs grown in sandy loam in a rangeland site in south-central Wyoming, USA. Powell et al. (1992) observed average second-year survival rates of around 97% for ponderosa pine, Rocky Mountain juniper (*Juniperus scopulorum* Sarg.), and Siberian peashrub LSFs in southeastern Wyoming, with similar soil and climatic conditions as those reported in Sturges (1983). While no studies to my knowledge have documented shrub-willow survival in LSF plantings, Gamble et al. (2014) found 96% post-coppice survival rates for *S. purpurea* ‘Fish Creek’ grown in hedgerows in alley cropping systems at two sites in southern Minnesota. In willow growth trials in central Minnesota, Zamora et al. (2014) observed post-coppice survival rates of approximately 90 % and 80 % for *S. purpurea* ‘Fish Creek’ and *S. purpurea* × *S. miyabeana* ‘Oneonta’, respectively.

The performance and survival of shrub-willows in our study was likely influenced by the presence of competing annual and perennial weeds in the study area during the first and second growing seasons. Despite post-emergent herbicide applications, a total of 32.5 man hours were spent hand-weeding the study site during the first two years of establishment. If established without best management practices, this high degree of maintenance is a primary drawback for shrub-willow LSFs (Heavey 2013). As a pioneer species, willows require full sunlight and intensive weed control for optimal survival and growth during the first few years of establishment (Kuzovkina and Quigley 2005; Abrahamson et al. 2010; Heavey 2013). Therefore, while willow survival in the study LSF was adequate two years after planting, proper pre-emergent weed control the year before planting, the use of weed barrier fabric, or mulch application may have improved survival rates and reduced the need for manual weed removal.

In addition to survival, the height of a snow fence also influences the snow storage capacity of a LSF, as height is proportional to a snowdrift’s cross-sectional area (Tabler 2003). The average height in our willow LSF treatments was approximately 1 m after one growing season post-coppice. This is lower than heights observed for two-year-old (one growing season post-coppice) willow LSFs in New York State, where the mean height for varieties *S. miyabeana* ‘SX64’ and *S. purpurea* ‘Fish Creek’ was 1.9 m (Heavey 2013; Heavey and Volk 2014). While this difference may be due to a number of factors, such as different soil and climatic conditions or variety selection, this could also be a result of insufficient weed control at the study site, as Heavey and Volk (2014) selected LSFs that were established with best management practices. Another factor that may have influenced willow growth at the study site is the tendency for right-of-way soils to be compacted as result of road construction. While I did not assess soil properties related to this in the current study, Souch et al. (2004) noted a 12 % reduction in stem biomass of *S. viminalis* under heavily compacted sandy loam relative to a control, but found the effect of moderate compaction to be insignificant on willow growth in clay loam and sandy loam. Although willows are generally known to tolerate harsh soil conditions (Kuzovkina and Volk 2009), future willow LSF studies should investigate soil physical properties, such as bulk density and porosity, as they relate to establishment. Nevertheless, willows at our site had comparable heights to coniferous and deciduous LSF species after eight growing seasons in Wyoming (Powell et al. 1992), and were taller than most LSF species after five growing seasons in separate study in Wyoming (Sturges 1983). While trees and shrubs in Wyoming likely experienced harsher growing conditions than in the current study, willows in this study tended to have faster growth rates, which Heavey and Volk (2014) also noted when comparing LSF shrub-willow growth rates to species traditionally used in LSFs.

When comparing heights among willows and rows in the snow fences, I observed an edge effect between the outer and inner rows, with outer rows tending to be shorter than inner rows. Interestingly, the converse trend was found by Gamble et al. (2014) during the establishment of multi-row poplar hedges in alley cropping systems, wherein edge trees tended to be larger than center trees. Moreover, this trend was only observed for north-south hedges and not east-west hedges (Gamble et al. 2014), which was the orientation of our LSFs. Other than Gamble et al. (2014), little information exists on differences among row establishment in windbreaks. Differences in wind stress were likely negligible between exposed outer rows and inner rows, as outer rows were observed to be relatively porous during the first growing season and thus likely offered little wind protection for inner rows. Furthermore, Sturges (1983) found no differences between the establishment of LSFs with and without the wind protection of an upwind structural snow fence. It is possible that weeds adjacent to the plot boundaries competed with outer rows for light, nutrients or moisture, as these areas were not cultivated. Herbicide drift from adjacent fields and rights-of-way or soil compaction from machinery could have also stunted outer rows. Ultimately, more research is needed to explain the cause of these edge effects.

As with snow fence height, porosity is a structural variable that determines the geometry of snow drifts around a fence (Tabler 2003). Measured porosity at our study was high overall, with an average of 83%. As expected, porosity was lower in four-row arrangements than in two-row arrangements. The average porosity for two-row arrangements in this study (87%) agreed with the average 88% porosity found for two-year-old (one growing season post-coppice), two-row willow snow fences in New York State (Heavey and Volk 2014). Living snow fences with four-row arrangements in this study had a significantly lower porosity (79.9%) than two-row arrangements. Tabler (2003) identified a porosity of 50% as contributing to the greatest snow storage capacity; however, the ideal porosity for a LSF may be higher or lower depending on the height of the LSF and mean annual snow transport for the site of the LSF. That porosity did not differ significantly among willow varieties corroborates Kuzovkina and Volk (2009) and Isebrands et al. (2014) who suggested that many willow varieties share morphological characteristics suitable for LSFs, such as relatively consistent porosity along the height of the plant.

The height and porosity of a LSF can be used to predict its snow storage capacity (Q_c), which can then be compared to the mean annual transport (Q) for the LSF's location to determine its overall functionality (Tabler 2003; Heavey and Volk 2014). At the study location, a Q of 39.9 t m^{-1}, classified as "light to moderate" snow transport (Tabler 2003), was observed over a snow accumulation season (SAS) of Nov 16 to Mar 17. These values agree with a range of Q and SAS dates found across southern Minnesota (Shulski and Seeley 2001; 2004). Values of Q_c in our study ranged from <1–9 t m^{-1}, which were comparable to those found for one- and two-year-old shrub-willow LSF in New York State (Heavey and Volk 2014). By comparing Q_c to Q, none of the current study's willow LSFs, regardless of variety and planting arrangement, was able to match or exceed Q at the study site after two growing seasons. At most, four rows of *S. purpurea* 'Fish Creek' could potentially trap 24% of Q at the study location. That none of the Q_c

values were equal to or greater than Q after one growing season post-coppice is consistent with the findings of Heavey and Volk (2014). They found that Q_c values for shrub-willow LSFs were unable to exceed local transport conditions until three years after planting. It is important to note that in all sample locations in Heavey and Volk (2014), Q was classified as “light” to “very light” (Tabler 2003) with none of the estimated Q values exceeding 20 t m^{-1}. In Minnesota, however, wind-defined snow transport conditions tend to be heavier than those reported by Heavey and Volk (2014), especially in western and southern Minnesota (Shulski and Seeley 2004). As such, LSFs in western and southern Minnesota may require additional years of growth before they are able to exceed Q values.

By applying models developed by Heavey and Volk (2014) relating two-row willow LSF age to height and porosity, I found that two-row willow LSFs could exceed the Q for the study location after four growing seasons (three growing seasons post-coppice) by approximately 113%. Incorporating this study’s relationship between number of rows and porosity, I observed that the Q_c of four-row arrangements could exceed Q after three growing seasons (two growing seasons post-coppice) by approximately 35% and by 149% after four growing seasons. The probability of annual snow transport exceeding Q by 100% is less than 0.1% (Tabler 2003; Heavey and Volk 2014); thus, predicted Q_c values for both two- and four-row planting arrangements could potentially exceed a twofold increase in Q after three growing seasons post-coppice. While these estimates may be useful in projecting future Q_c values, they are based on willow growth in New York State, which likely has some differences in growth conditions. Additionally, willows LSFs used by Heavey and Volk (2014) to develop the height and porosity regressions were not harvested, so these estimates may not be applicable to willows harvested on a short rotation. Therefore, future research should document willow LSF growth and porosity to evaluate the model estimates.

I observed throughout the winter of 2014-2015 that all willow plots were trapping snow, and that four rows tended to catch more snow than two rows. However, I was not able to compare the snow measurements to the modeled Q_c results. The models developed by Tabler (2003) assume there are few days with above-freezing temperatures between the onset and end of the SAS. With this assumption, measurements taken at the end of the SAS should provide the total amount of snow trapped by a LSF during the SAS (e.g., Shulski and Seeley 2001). In this study, there were many dates during the 2014-2015 SAS in which temperatures were above freezing, as well as rain events. This prevented me from obtaining total SAS measurements, but did allow for comparison among willow varieties and planting arrangements. These measurements confirmed my expectation that LSFs with four rows capture more snow than LSFs with two rows, likely due to the generally lower porosity in four rows. Willow variety ultimately had no effect on observed snow storage capacity, which may be explained by the lack of a variety effect on porosity. These observations suggest that, for early snow storage capacity, four rows of willows are more effective than two rows. Additionally, since willow variety had no effect on snow capture, multiple varieties may be appropriate in a LSF, which could improve a LSF’s resiliency to disease, pest outbreaks or other disturbances (McCracken et al. 2001; Mundt 2002). Furthermore, this could allow varieties to be selected for LSFs based on site-specific factors. Ultimately, these implications should be evaluated in future studies.

1.5 Conclusion

In comparing the effectiveness of willow LSFs with three different willow varieties and two different planting arrangements, I found all planting designs to have adequate survival and growth after one growing season post-coppice. However, establishment could likely be improved with proper weed control practices. Furthermore, care should be taken to prevent herbicide drift around LSFs as I did observe dieback and lower growth on edge rows. Although this could not be attributed specifically to herbicide drift, preventing herbicide drift is a best management practice during LSF establishment (Shaw 1988) and may have improved edge-row establishment in this study.

Porosity of willow LSFs after one growing season post-coppice was high across all treatments, but on average lower in four-row planting arrangements than two-row arrangements. Using models by Tabler (2003), measured height and porosity for willow LSF varieties and planting arrangements translated to low overall Q_c values relative to Q. Using models from Heavey and Volk (2014), however, I found that willow LSFs could exceed Q in three to four growing seasons after planting. Although I was unable to evaluate model predictions with field measurements, field measurements revealed that all willow LSFs were trapping snow throughout the 2014-2015 winter and that four-row planting arrangements trapped more snow than two-row arrangements, as expected. Willow variety did not have an effect on measured snow transport, suggesting that multiple shrub-willow varieties could be used in LSFs based on site-specific factors. Ultimately, these finding should be evaluated in future years and studies, especially during winters with consistently below-freezing temperatures. Overall, these results add to the literature that shrub-willows are an appropriate choice for LSFs (Heavey and Volk 2014, Kuzovkina and Volk 2009).

Chapter 1 Tables

Table 1.1 Selected soil characteristics for living snow fence establishment in Waseca, Minnesota, USA.

Soil type	Soil depth (cm)	pH	Electrical conductivity (µS/cm)	Particulate organic matter (%)	C/N ratio
Clay loam	0-15	6.9	265	3.3	12.45
	15-30	6.6	228	2.0	12.06
	30-45	6.6	205	1.8	12.63
	45-60	6.7	211	1.6	12.41
	60-75	7.0	182	1.6	12.26
	75-90	6.8	146	1.6	11.76

Values are the average of three composite samples taken for each 15 cm depth increment

Table 1.2 Number of days with snowfall, rainfall, and above-freezing temperatures during the 2014-2015 snow accumulation season at the Southern Research and Outreach Center in Waseca, Minnesota.

Month	Days with snowfall	Days with rainfall	Days with temperatures above 0ºC
November	7	2	4
December	5	3	13
January	8	2	10
February	9	1	4
March	2	0	11

Data collected from the weather station at the Southern Research and Outreach Center (SROC 2015) and MnDOT Waseca Truck Station (MnDOT 2015)

Table 1.3 Height, porosity, potential snow storage capacity (Q_c) and ratio of Q_c to mean annual snow transport (Q) for 6 willow living snow fence treatments after one growing season post-coppice. Values in parentheses are the standard error of the mean.

Number of rows	Species	Height m	Porosity %	Q_c t m^{-1}	Q_c:Q (x:1)
Two	Fish Creek	1.0 (0.04)	88 (0.8)	<1	<0.01
	Oneonta	1.1 (0.06)	88 (1.6)	<1	<0.01
	S365	0.8 (0.03)	85 (1.1)	<1	0.02
Four	Fish Creek	1.3 (0.03)	76 (1.7)	9.4	0.24
	Oneonta	1.1 (0.03)	85 (1.5)	1.7	0.04
	S365	1.0 (0.02)	79 (1.9)	3.9	0.10

Height rounded to the nearest tenth of a m, porosity rounded to nearest whole percentage, Q_c rounded to nearest tenth of t m^{-1}, and actual Q_c:Q rounded to nearest hundredth

Table 1.4 Predicted height, porosity, potential snow storage capacity (Q_c) and ratio of Q_c to mean annual snow transport (Q) for two- and four-row willow snow fences at two, three, and four years after planting based on willow living snow fence models.

Number of rows	Years after planting[a]	Height[b] m	Porosity %	Q_c t m^{-1}	Q_c:Q (x:1)
Two	2	2.0	85[c]	6.7	0.17
	3	2.6	78	37.3	0.93
	4	3.2	70	84.9	2.13
Four	2	2.0	77[d]	21.7	0.54
	3	2.6	71	53.7	1.35
	4	3.2	65	98.9	2.48

Height rounded to the nearest tenth of a m, porosity rounded to nearest whole percentage, Q_c rounded to nearest tenth of t m^{-1}, and actual Q_c:Q rounded to nearest hundredth

[a] Years after planting refers to the age of the root system; willows are assumed to be coppiced after the first growing season

[b] Height was predicted by willow LSF growth models developed by Heavey and Volk (2014)

[c] Two-row porosity was predicted by willow LSF porosity models developed by Heavey and Volk (2014)

[d] Four-row porosity was predicted by Heavery and Volk's (2014) porosity and modified by (Equation 2) in this study

Table 5 Mean snow storage measurements in willow snow fences by number of rows and month during 2014-2015 winter.

Number of rows	November	January	March
		t m^{-1}	
Two	0.98	3.24	2.48
Four	0.93	3.97	3.25

Chapter 1 Figures

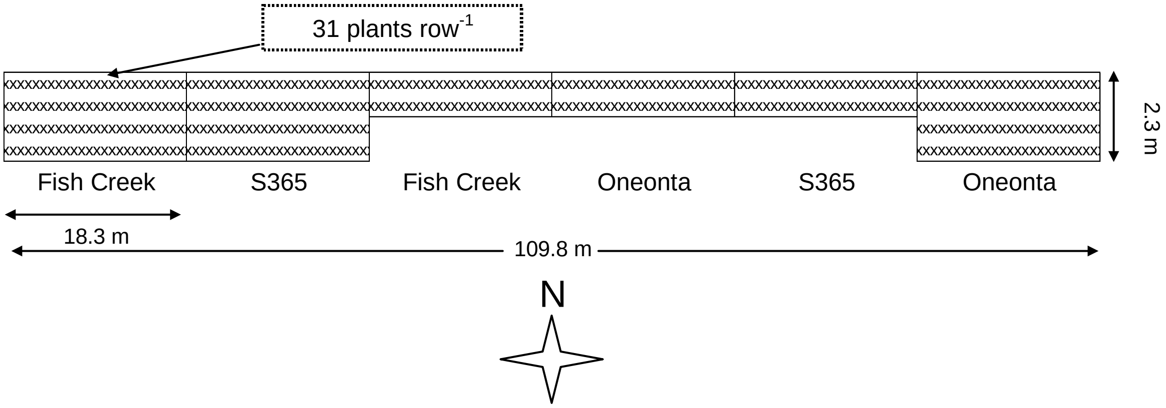


Figure 1.1 Example replicate of willow living snow fence experiment in Waseca, Minnesota.

Figure 1.2 Using a large red backdrop to assess porosity in shrub-willow living snow fences.

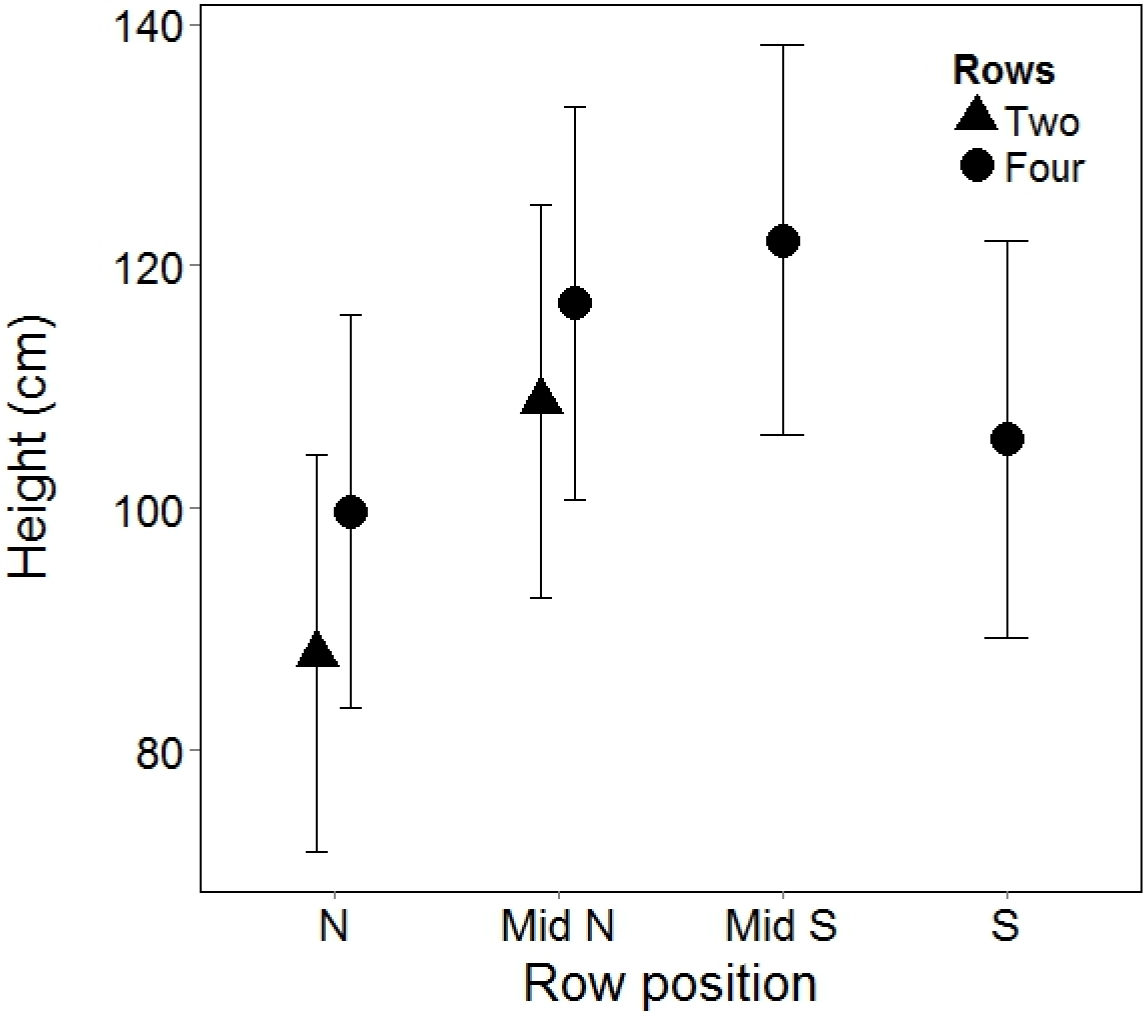
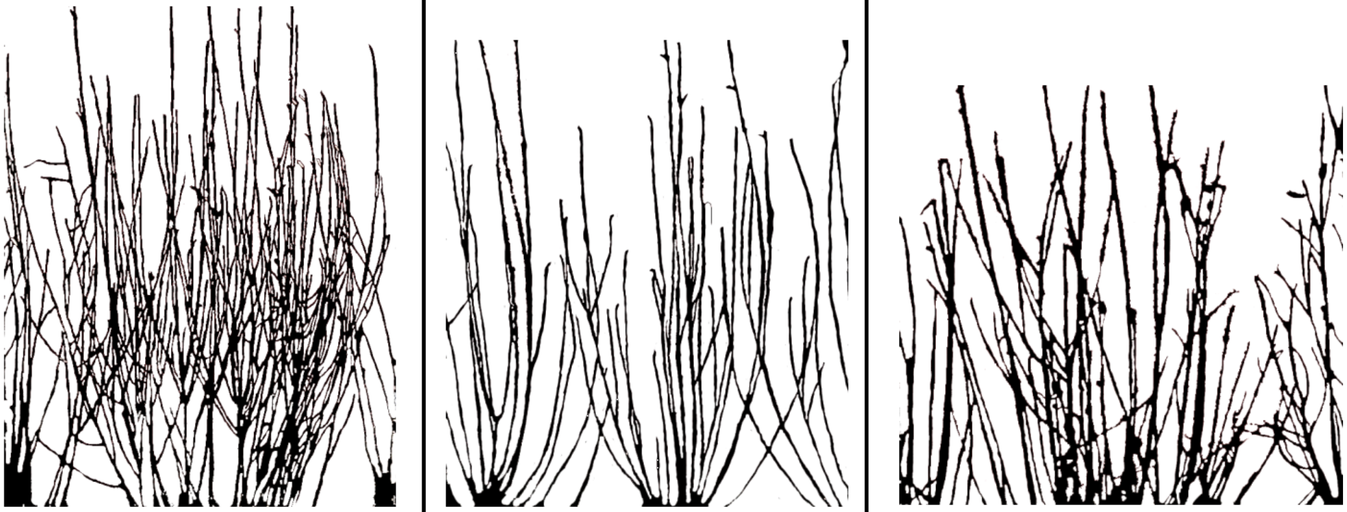


Figure 1.3 Mean heights across varieties for row positions in willow living snow fences with two- and four-row planting arrangements, where "N" is the northernmost row and "S" the southernmost row. Error bars represent 95% confidence intervals.

2 row Fish Creek (88.1%)

2 row Oneonta (88.4%)

2 row S365 (85.4%)



4 row Fish Creek (76.3%)

4 row Oneonta (84.7%)

4 row S365 (78.6%)

Figure 1.4 Selected porosity images that closely resemble the average porosity (in parentheses) for each willow variety and planting arrangement. Images presented do not necessarily imply statistical differences.

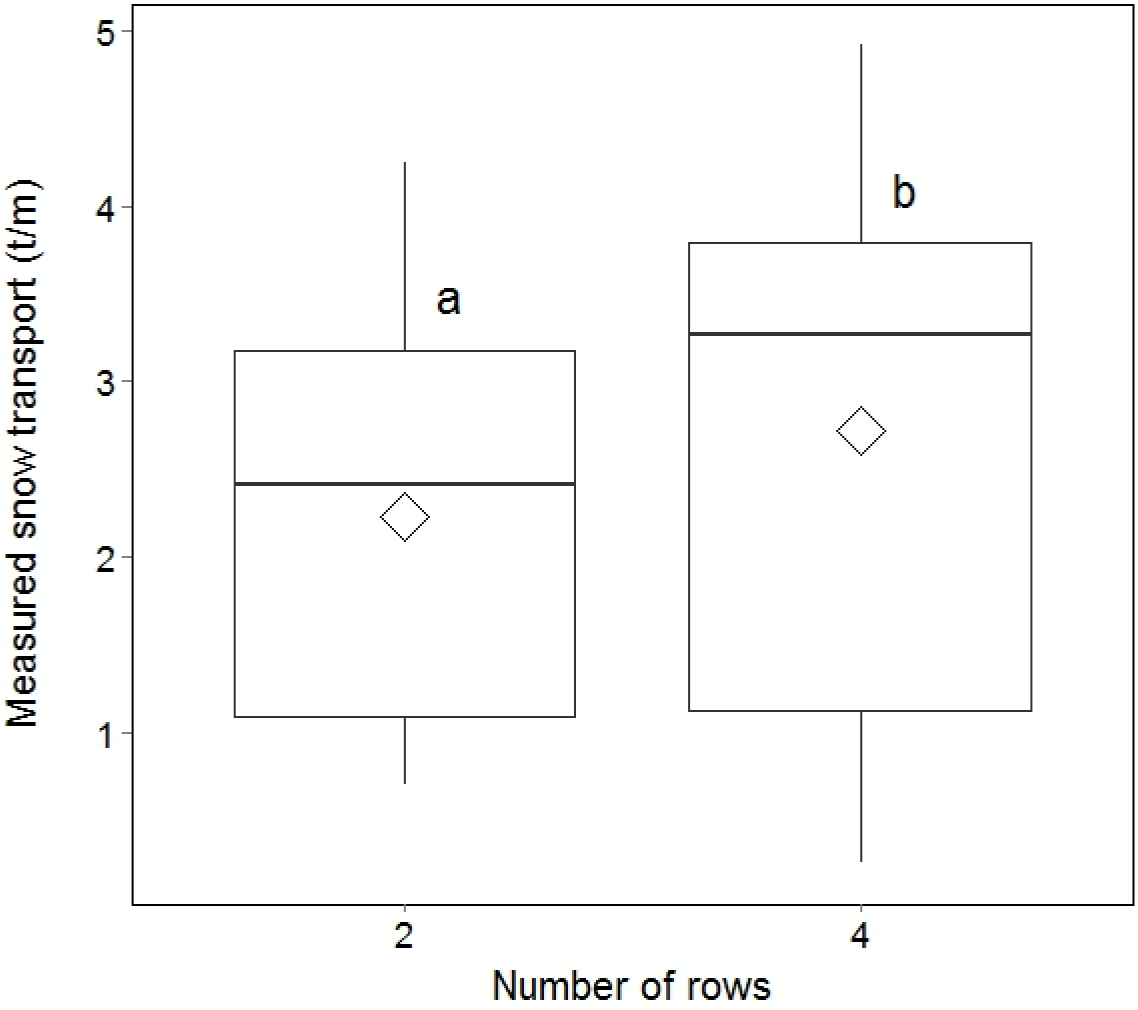


Figure 1.5 Box-and-whisker plots for measured snow transport between Dec 2014 and Mar 2015 in two- and four-row planting arrangements across willow varieties. Diamonds represent the mean for each planting arrangement. Different letters indicate significant difference under Tukey's HSD test at *P*<0.001.

CHAPTER 2: ESTABLISHMENT AND GROWTH OF NATIVE AND HYBRID SHRUB-WILLOWS, GRAY DOGWOOD, AND AMERICAN CRANBERRYBUSH FOR USE IN LIVING SNOW FENCES

2.1 Introduction

Willows (*Salix* spp.) have provided numerous societal and environmental benefits dating back to ancient civilizations. During the Roman Empire, they were cultivated for use in baskets, fences, medicine and building construction (Volk et al. 2006). Similar uses of willows are found among the indigenous people of North America: in 8000 BC, the Ojibwe, for example, relied on willow for heating, cooking, shelters, and medicine (which was later developed into aspirin) (Isebrands and Richardson 2014). Willows were also utilized for soil stabilization and along irrigation canals by the Hohokam of Mexico in 800 AD (Isebrands and Richardson 2014).

More recently, willows have undergone intensive research efforts for use in a broad suite of environmental applications. This is due to a number of their ecological and physiological adaptations. As a pioneer species, willows can rapidly establish on disturbed, nutrient-poor sites, making them suitable for marginal lands (Kuzovkina and Quigley 2005). Their physiological characteristics include fast juvenile growth, ease of vegetative propagation from root primordia on their stems, and rapid re-establishment from coppiced stools (Kuzovkina and Quigley 2005). Additionally, willow possess large genetic variation within individual species, allowing for hybridization via crosspollination. This has resulted in many hybrids with attributes desirable for a range of applications (Kuzovkina and Volk 2009).

Willows have been employed worldwide in environmental applications including wetland restoration, wildlife habitat, phytoremediation, streambank stabilization, and biomass production for bioenergy. Biomass production with willows has been an especially growing field of study, given willows' potential for high biomass yield and potential to contribute to sustainable rural development (Volk et al. 2006; Isebrands and Richardson 2014; Zamora et al. 2015).

While much is known about willow uses and cultivation, more work is needed to evaluate willow species under different site conditions and for different purposes. One such purpose is living snow fences. Living snow fences (LSFs) are windbreaks planted to keep snow and ice from blowing off of farm fields and onto adjacent roads. They do this by creating wind turbulence along the length of their barrier, causing blowing snow and ice particles to deposit around the fence in drifts instead of in the protected roadway. Without protective barriers, blowing snow can create hazardous road conditions and contribute to high snow removal costs (Tabler 2003). While LSFs can be cost-effective solutions to reducing blowing snow on roadways, especially more so than structural snow fences (e.g., metal or wooden fences), their adoption by landowners is limited (Wyatt et al. 2012). Landowners have expressed concerns about LSFs related to removing arable land, risk of plant mortality, and time spent installing and maintaining LSFs (Wyatt et al. 2012).

Willows have been proposed as a LSF candidate due to their ease of planting, fast establishment and growth, ability to produce dense, small-diameter stems for trapping snow (Kuzovkina and Volk 2009), and potential to provide a marketable biomass product. Furthermore, by producing dense barriers in closely spaced double-row arrangements, shrub-willows can potentially reduce the area needed for a LSF (Isebrands et al. 2014). Initial studies on shrub-willow LSFs indicate they can provide fully effective barriers approximately 3 years after establishment (Heavey and Volk 2014; Ogdahl et al. in review), while snow capture has been observed as soon as 2 years after establishment (Isebrands et al. 2014; Ogdahl et al. in review). This relatively early snow storage ability contrasts with many species traditionally used in LSFs, such as spruce (*Picea spp.*) or juniper (*Juniperus spp.*), which can require 5 to 20 years before functioning as effective LSFs (Sturges 1983; Powell et al. 1992; Tabler 2003).

As part of evaluating the use of shrub-willows for LSFs (see Ogdahl et al. in review), the current study sought to compare the establishment and growth of hybrid willow varieties tested in Minnesota LSFs to a willow species native to Minnesota (*Salix petiolaris*) and two species traditionally used in LSFs in Minnesota, American cranberrybush (*Viburnum opulus* L. var. *americanum* Ait.) and gray dogwood (*Cornus racemosa* Lam.). Both of the traditional LSF species are bushy shrubs with numerous stems that can reach heights up to 5 m (Smith 2008), thereby producing dense, tall barriers for trapping snow in linear plantings. However, the time required for cranberrybush and dogwood shrubs to reach effective heights may be longer than that required for shrub-willows. In the literature, for cultivated and wild populations, American cranberrybush and gray dogwood have reported annual height growth rates of 24-36 cm year^{-1} (St-Pierre et al. 2005) and 4-20 cm year^{-1} cm (Boeken and Canham 1995), respectively, although these values only cover a narrow range of biotic and abiotic conditions. For shrub-willows, annual height growth can be as high as 1-3 m year^{-1}, depending on site conditions (Amichev et al. 2014, Gamble et al. 2014). No studies, however, have compared the growth of shrub-willows to traditional LSF species in a similar environment. It was hypothesized that the growth of all shrub-willows would exceed the growth of the traditional LSF species.

The purpose of testing the native willow (*S. petiolaris*) was to address concerns over the promotion of non-native plants in LSFs, as well evaluate the potential for using local plant sources for LSFs. With over 450 species worldwide (Argus 1997), willows are adapted to a range of site and climatic conditions and can often provide a local source for a range of environmental applications (Kuzovkina and Quigley 2005). Minnesota has 18 species of native willows growing throughout the state (Smith 2008). Given their distribution and abundance, native willow species may provide a suitable local plant source for LSFs in Minnesota. However, no research has yet been done to assess their potential for LSFs in Minnesota. It was hypothesized that *S. petiolaris* would be similar in growth to the hybrid willow varieties, given its adaptation to the local growing conditions (Smith 2008).

Lastly, this study sought to evaluate whether coppice timing (e.g., fall or spring) influences establishment and growth in the willows, in order to determine whether it is advisable to leave first-year stem growth over the winter and coppice the following spring, such that first-year stems may serve as a snow barrier. In theory, there should be no difference in growth among coppice dates as long as willows are dormant (Abrahamson et al 2010.), but growth in most willow studies is based on a fall coppice, likely due to easier field access in the fall. This has resulted in little information on growth after a spring coppice. No differences in growth were expected between a fall and spring coppice date.

2.2 Methods

2.2.1 Study site description

The study was located in Waseca, Minnesota, at the University of Minnesota's Agricultural Ecology Research Farm (44^{o}03'48" N; 93^{o}32'42" W), which is part of the Southern Research and Outreach Center (SROC). Soils at the site are of the Nicollet series (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls) and were formed in loamy, calcareous till and are very deep and well-drained to very poorly drained. The site ranges in slopes between 0 and 5%. Soil characteristics for the study site are presented in (Table 3.1). Prior to establishment, the site was under a drainage study with perennial crops. The site was rototilled in June 2013, approximately one week before planting.

2.2.2 Experimental design and planting materials

The study was established in a randomized complete block design in a split plot arrangement with five willow cultivars and two shrub species traditionally used in LSFs in Minnesota (Table 3.2). The study had four replicates with willow cultivars randomly assigned to either a fall or spring coppice treatment, while cranberrybush and dogwood plots were not coppiced, based on standard management practices (Figure 3.1). Hybrid willow cuttings and bare-root plants were obtained from two commercial nurseries (Double A Willow Inc., Fredonia, NY, and Shumacher's Nursery and Berry Farm, Inc., Heron Lake, MN, respectively), while native willow cuttings were collected from dormant plants at the Ottawa Wildlife Management Area near St. Peter, MN. The use of the native willow, *S. petiolaris*, was recommended by state botanist W. Smith (personal communication) based on its prevalence in the local area.

The study was established with plots 5.3 m by 5.5 m. Willow plots were planted with 20 cm (8 inch) dormant stem cuttings in a high-density arrangement of three twin rows, following standard willow trial plot guidelines (Cameron et al. 2008). Twin rows were spaced 150 cm apart, single rows 76 cm apart, and plants within a row 60 cm apart for a density of 14,800 willow cuttings ha^{-1}. Dogwood and cranberrybush plots were planted in 5 single rows with 1.2 m between rows and 1.2 m between plants within a row, based on conservation planting guidelines (NRCS 2009), resulting in a density of 6,727 bare-root plants ha^{-1}. Willow plots assigned to a fall coppice were coppiced in December 2013, while those assigned to a spring coppice were coppiced in April 2014.

Shortly after planting, the site was managed for post-emergent weeds. In 2013, willow plots were sprayed with 0.3 kg ha^{-1} a.i. clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) and 0.2 kg ha^{-1} a.i. sethoxydim {2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one} to control post-emergent weeds, while dogwood and cranberrybush plots were treated with 0.2 kg ha^{-1} a.i. sethoxydim only. In 2014, all plots were sprayed with 0.3 kg ha^{-1} a.i. clopyralid and 0.2 kg ha^{-1} a.i. sethoxydim. Additionally, plots were cultivated in July 2013, followed by manual weed control throughout the remainder of the growing season. All plots were assessed for survival approximately one month after planting; plants without any visible growth were replaced with fresh cuttings or bare-root plants to ensure sufficient stocking.

2.2.3 Plant data collection

To evaluate shrub establishment, survival was assessed approximately one month, one growing season (pre-coppice), and two growing seasons (post-coppice) after planting. For the first assessment, all plants were surveyed for visible growth and restocked accordingly. In following assessments, sample plots were used. In willow plots, twelve central plants were assessed in the middle twin row, and 9 central plants were assessed in dogwood and cranberrybush plots.

To assess and compare plant growth, stem counts, diameters and heights were measured in the fall of 2013 and fall of 2014 (pre- and post-coppice, respectively) in the designated sample areas. For all plants in the sample area, the height of the tallest stem was recorded to the nearest centimeter, following standard willow measurements (Cameron et al. 2008). Stem diameters were recorded to the nearest millimeter at 30 cm above the ground for all stems greater than 3 mm, except when only stems less than 3 mm were present.

2.2.4 Statistical analyses

Linear mixed effects models were used to examine the effects of species and year on survival, height, stem count, and stem diameter for all shrubs. For willows only, linear mixed effects models were also used to examine the effects of willow species/cultivar and coppice date on 2014 survival, height, stem count, and stem diameter. For each parameter, species and year (or willow species and coppice date) were included as fixed effects and tested for significance and interaction via Wald's Chi-square test. To account for the nested structure in both datasets, replicate and plot number were included as random effects (Pinheiro and Bates 2000). Where main effects were significant at $\alpha = 0.05$, Tukey's honestly significant difference (HSD) for multiple comparisons was used to test for differences among means at $\alpha = 0.05$. All statistical analyses were performed in R (v. 3.0.2; R Foundation for Statistical Computing, Vienna, Austria).

2.3 Results

2.3.1 Growth variables by species and year

Significant main effect of species ($P < 0.001$) and year ($P = 0.02$) were observed on shrub survival, without an interaction (Table 3). On average, survival decreased from

92% in 2013 to 88% in 2014 (*P* = 0.023). By 2014, survival among species and cultivars was not statistically different, although Fish Creek had the overall highest survival.

A significant interaction was found between species and year (*P*<0.001) on shrub heights. In 2013, willow cultivars/species Fish Creek and Oneonta were among the tallest species, while willow cultivar S25 was more similar to the shorter heights of cranberrybush and dogwood (Table 3.3). From 2013 to 2014, the heights of all willows significantly increased, while the height of cranberrybush and dogwood did not increase significantly. In 2014, all willows were significantly taller than traditional snow fence shrubs, with Oneonta, *S. petiolaris* and Fish Creek having the tallest heights.

As with height, shrub stem counts and diameters were influenced by the interaction of species and year (*P*<0.001). From 2013 to 2014, all willows significantly increased in their number of stems and stem diameters, while there was no significant change in cranberrybush or dogwood stem counts or diameters. Willows also had more stems and larger diameters than dogwood and cranberrybush shrubs in 2014.

2.3.2 Effects of coppice timing on 2014 willow growth variables

I did not observe any effect of species or coppice date on willow survival. The interaction of species and coppice date did, however, influence height (*P* = 0.013) and the number of stems per plant (*P* < 0.001) (Table 3.4). For plant height, coppice time only had a significant effect on Fish Creek, for which plants coppiced in fall 2013 were taller than plants coppiced in spring 2014. Regarding the number of stems per plant, coppice time significantly affected Fish Creek, for which there were more stems under a fall coppice, and S25, for which there were more stems under a spring coppice. Mean stem diameter was not significantly influenced by coppice date, resulting in the same observations provided in Table 3.3.

2.4 Discussion

Shrub establishment was generally good among species, although little increase in growth occurred in cranberrybush and dogwood shrubs after the first growing season. I observed high overall survival rates among shrubs after the first growing season, but saw an overall decrease in survival after the 2014 growing season. For willows, a slight decrease in survival is not uncommon after coppicing (e.g., Zamora et al. 2014). For cranberrybush and dogwood shrubs, it is possible they were affected by herbicide application in the second year, as they were observed as being wilted at the start of the 2014 growing season, shortly after herbicide application (Figure 3.2). In the first year, at the start of the growing season, cranberrybush and dogwood plots received only an a.i. sethoxydim herbicide treatment, but in the second year they received both an a.i. clopyralid and a.i. sethoxydim treatment. It is likely that a.i. clopyralid stunted cranberrybush and dogwood shrubs, as it is not registered for use on either dogwood or cranberrybush shrubs (Gullickson et al. 1999).

Other factors that may have influenced survival were the occurrence of droughts during both growing seasons, as well as the presence of competing vegetation. Willows are especially water-limited (Thelemann et al. 2010), and drought can significantly decrease willow survival (Zamora et al. 2014). Additionally, due to the lack of pre-emergent herbicide application the year prior to establishment, as recommended for willow plantings (Abrahamson et al. 2010), shrubs experienced competition among annual and perennial weeds, which is the most common cause of willow failure in the first two growing seasons. Nevertheless, at the end of 2014, all shrubs except for S25 had survival rates above the 80% threshold recommended for productive SRWC stands Bergkvist et al. (1996).

After the second growing season, willows exhibited significantly higher growth than cranberrybush and dogwood shrubs, with a mean height 4 times greater than that of the traditional LSF shrubs. This is to be expected, as it is not uncommon for shrub-willows to grow 1-3 m during a growing season (Amichev et al. 2015, Gamble et al. 2014), while cranberrybush and dogwood shrubs tend to have lower growth rates. Interestingly, however, neither cranberrybush nor dogwood shrubs increased in growth with regard to height, number of stems, and stem diameter from 2013 to 2014. This again is likely explained by the Transline herbicide application in 2014. Willows, however, had no observable response to the herbicide applications.

Within willows, second-year (one growing season post-coppice) growth characteristics of the varieties were similar to those found in Amichev et al. (2015), who assessed early growth in the same willow varieties in central Saskatchewan, Canada. For Fish Creek, Oneonta, S365, and S25, they found mean heights of 165.5 cm, 97.4 cm, 116.6 cm, and 141.1 cm, respectively; mean stem counts per plant of 9, 8, 9.2, and 7.3, respectively; and mean diameters 6.3 mm, 4.1 mm, 5.6 mm, 6.5 mm, respectively (Amichev et al. 2015). Regarding the native willow (*S. petiolaris*), little information exists on its growth characteristics in a cultivated setting. Labrecque et al. (1997) found biomass yields of *S. petiolaris* to be significantly lower than *S. discolor* Mühl and *S. viminalis* L. after two growing seasons near Montreal, Canada, but did not report height or stem measurements. In wild populations in Minnesota, *S. petiolaris* can reach heights of 4 m and basal diameters of 4 cm (Smith 2008). In this study, I found the growth of *S. petiolaris* was comparable to willow cultivars with the highest growth. This in some ways contrasts to findings of Zamora et al. (2014), who found native willows different than ours to possess lower survival rates, growth rates, and biomass production than hybrid willows in central Minnesota. However, given that *S. petiolaris* is perhaps the most common and abundant willow in Minnesota (Smith 2008) and was collected from a local source and thus well-adapted to local conditions, it is somewhat unsurprising that it was comparable to genetically improved willows in this study.

Salix petiolaris may be an appropriate native willow for LSF plantings. When selecting species or varieties for a living snow fence (LSF), it is important to consider the morphological characteristics of the species. Creating a LSF with a consistent optical porosity throughout the length and height of a LSF is desirable for consistent snow trapping efficiency and downwind drift length throughout the LSF (Volk et al. 2006; Kuzovkina and Volk 2009). Too much variability in these factors could lead to inconsistent road protection from snow drifts. An advantage of hybrid willow varieties is that they tend to have relatively consistent optical porosity and growth for a given planting arrangement in a LSF (Ogdahl et al., in review). Native willows, especially from different genetic sources, may have more variability in these morphological characteristics, given their potential for hybridization (Argus 1997). However, native willows propagated from clonal cuttings of a parent plant with desirable LSF traits could guarantee a relatively consistent height and porosity throughout a LSF. If only a single parent plant is used, a disadvantage of this approach would be a lack of genetic diversity among the propagated plants, which could potentially limit a LSF in its resistance and resilience to diseases or disturbances. Thus, identifying multiple parent plants with similar morphological characteristics may be important for creating a native willow LSF consistent in height and porosity and resilient to diseases or other disturbances. Given the abundance of *S. petiolaris*, as well as the presence of 18 species of native willows, throughout Minnesota (Smith 2008), finding a suitable LSF source within a given region should be feasible. Native willows may then be capable of providing a local and affordable plant source for LSF plantings around Minnesota.

Regarding the effects of coppicing in willows, all willows significantly increased in the number of stems per plant after coppicing, which is typically observed throughout willow production trials. In a LSF context, an increase in the number of stems would decrease the porosity of a LSF, which would likely increase a LSF's snow storage. Regarding coppice date, few differences were observed between the fall 2013 coppice and spring 2014 coppice. Fish Creek, however, had significantly lower height and stem counts under the spring 2014 coppice, whereas the converse was true regarding stem counts in S25. It is possible that Fish Creek may be active earlier in the growing season than other willows, and therefore already allocated some its resources to growth at the time of coppice. This has yet to be tested, however, and no new leaves were observed at the time of the spring coppice, although some buds were present. That S25 had significantly more stems per plant under the spring coppice than under the fall coppice is interesting and not explained in the literature. Ultimately more research is needed to explain this observation and determine if it occurs at other sites. Other than Fish Creek and S25, coppice date had little effect on willow growth, which agrees with the literature. According to Abrahamson et al. (2010), for example, coppicing can occur anytime between two weeks after leaf senescence and bud swelling in the spring. However, coppicing in the fall before snowfall may be easier logistically, as access to willow plots or an LSF will likely be easier due to the lack of snowdrifts or thawing ground. Furthermore, blowing snow has potential to damage young plants by tearing side-branches from the main stem (Heavey and Volk 2013). A fall coppice will also ensure there is no waste of plant growth in the case of unexpected early budding in the spring (Heavey and Volk 2013).

2.5 Conclusion

The goal in this study was to compare establishment and growth characteristics of shrub-willow LSF candidate species/varieties to shrub species traditionally used in LSFs. Additionally, this study sought to evaluate whether coppice timing influences establishment and growth in shrub-willows, in order to determine whether it is advisable to leave first-year stem growth over the winter and coppice the following spring, such that first-year stems may serve as a snow barrier. According to literature, there should be no difference in growth among coppice dates (Abrahamson et al 2010.), but growth in most willow studies is based on a fall coppice, likely due to easier field access in the fall, resulting in little information on spring coppice growth.

I found that all shrubs had good establishment, and that all willows outperformed the traditional LSF species. However, due to concerns about herbicide effects on the traditional LSF shrubs, it is difficult to conclude with certainty that willows did indeed outperform the other shrubs. Nevertheless, shrub-willows generally possess higher growth rates than cranberrybush or dogwood shrubs (e.g., Boeken and Canham 1995; St-Pierre et al. 2005).

Within willows, I found that the native willow, *S. petiolaris*, was comparable in growth to the highest performing cultivars Fish Creek and Oneonta. Given its wide range throughout Minnesota (Smith 2008), *S. petiolaris* may thus be suitable for living snow fence applications, although it should ultimately be tested in an LSF configuration before widespread adoption. Minnesota has 18 species of native willows throughout the state (Smith 2008); if they can provide effective LSFs, they may provide a local and affordable plant source for plantings around Minnesota.

Most willows showed no difference in response to coppice dates, but the two that did (Fish Creek and S25) showed opposite responses. Ultimately more research is needed to explain this. A spring coppice date may be suitable for most willow LSF candidates. In this study, some willow stems were noted as budding at the time of coppice (9 April 2014), meaning they had already allocated some of their annual growth. In an average year, a coppice in early March may be better (Abrahamson et al. 2010). However, access to LSFs may be easier in the fall, and there is less risk of wind or snow damage to dormant plants over the winter if coppiced in the fall. A fall coppice would negate any snow capture benefits from first year growth, but another form of snow control, such as plowing windrows or installing an artificial fence, could be employed during the first winter of establishment.

Chapter 2 Tables

Table 2.1 Selected soil characteristics for shrub establishment at the University of Minnesota's Agricultural Ecology Research Farm in Waseca, Minnesota.

Soil type	Soil depth (cm)	pH	Electrical conductivity (μS/cm)	Particulate organic matter (%)	C/N ratio
Clay loam	0-15	5.3	123	2.4	11.00
	15-30	5.2	98	2.3	11.28
	30-45	5.4	122	2.1	11.25
	45-60	5.6	156	2.5	11.20
	60-75	5.8	168	2.1	10.28
	75-90	5.8	179	1.8	10.06

Values are the average of three composite samples taken for each 15 cm depth increment

Table 2.2 Shrub species used in variety/species comparison study.

Species/hybrid plants	Common name	USDA Plant Hardiness Zones
Salix purpurea × *S. purpurea*[a]	Fish Creek	4–6
S. purpurea × *S. miyabeana*[a]	Oneonta	4–6
S. caprea × *S. cinerea*[a]	S365	4–6
S. eriocephala × *S. eriocephala*[a b]	S25	4–6
S. petiolaris[b]	Slender-leaved willow	NA[c]
Cornus racemosa Lam.[b]	Gray dogwood	3–8
Viburnum opulus L. var. *americanum* Ait.[b]	American cranberrybush	2–7

[a] Originated through controlled breeding in New York

[b] Native to Minnesota

[c] *NA* No available data on hardiness zone, but occurs throughout northeastern United States and much of Canada (Argus 2007)

Table 2.3 Mean survival, heights, stem counts, and stem diameters for shrub-willows and traditional living snow fence shrubs in 2013 and 2014.

Species/ cultivar	Plant type	Survival (%)		Height (cm)		Stem count plant^{-1}		Diameter (mm)	
		2013	2014	2013	2014	2013	2014	2013	2014
Fish Creek	Shrub-willow	100.0 a	100.0 a	75.0 a,r	175.2 a,s	1.8 a,r	7.8 a,s	3.8 a,r	5.7 a,s
Oneonta		85.4 ab	84.4 a	72.3 ab,r	201.4 a,s	2.2 a,r	10.5 b,s	3.9 a,r	7.0 ab,s
S365		82.3 ab	81.3 a	56.3 abc,r	127.7 b,s	1.8 a,r	8.1 a,s	4.2 a,r	6.6 ab,s
S25		84.4 ab	77.1 a	40.5 bc,r	118.3 b,s	1.2 a,r	6.1 a,s	3.7 a,r	6.1 ab,s
S. petiolaris		93.8 a	87.5 a	52.0 abc,r	176.0 a,s	1.6 a,r	6.1 a,s	3.5 a,r	7.2 b,s
Cranberry	Traditional snow fence shrubs	100.0 ac	94.4 a	34.5 c,r	34.7 c,r	1.1 a,r	1.6 c,r	3.3 ab,r	3.2 c,r
Dogwood		100.0 ac	94.4 a	37.0 c,r	43.2 c,r	1.0 a,r	0.8 c,r	2.3 b,r	1.9 d,r

Means with overlapping letters are not statistically different under Tukey's HSD at $p \leq 0.05$. Letters a-c denote differences among species, while letters r-s denote differences between years. Differences between years are only noted where there is a significant interaction between species and years.

Table 2.4 The effect of coppice time and species on 2014 mean willow height and number of stems per plant.

Species/cultivar	Height (cm)		Stem count plant^{-1}	
	Fall	Spring	Fall	Spring
Fish Creek	203.3 a,r	147.1 bc,s	11.5 a,r	4.2 b,s
Oneonta	194.1 a,r	207.9 a,r	10.8 a,r	10.2 a,r
S365	126.1 b,r	129.3 c,r	8.1 ab,r	8.1 a,r
S25	96.9 b,r	136.6 c,r	4.5 b,r	7.5 a,s
S. petiolaris	181.7 a,r	170.1 abc,r	6.9 ab,r	5.2 a,r

Means with overlapping letters are not statistically different under Tukey's HSD at $p \leq 0.05$. Letters a-c denote differences among species, while letters r-s denote differences between years.

Chapter 2 Figures

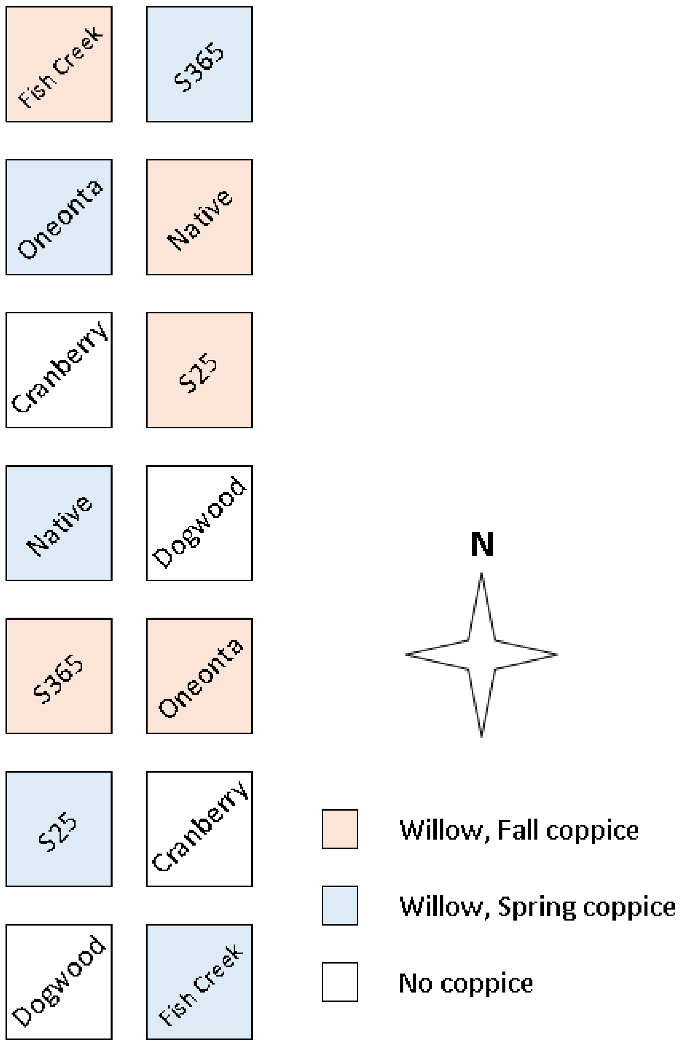


Figure 2.1 Example replicate for the comparison of candidate shrub species for living snow fences. All willows are represented by their common name provided in Table 3.2. "Native" refers to *Salix petiolaris*.

Figure 2.2 American cranberrybush with wilted leaves and stems in June, 2014, shortly after herbicide application.

CHAPTER 3: CONCLUSIONS

This research suggests that shrub-willows may provide effective living snow fences (LSFs) in Minnesota. In Chapter 1, willows were observed to have generally high survival and growth rates after two growing seasons, with the potential to trap all of the mean annual blowing snow at the site three to four growing seasons after planting. Additionally, I found willow LSFs with four rows tended to catch more snow than two-row LSFs, likely due to denser vegetation in four-row arrangements. Four-row arrangements may therefore be more useful for providing snow capture earlier on during LSF establishment than two-row arrangements. No differences were found among willow varieties in terms of snow capture, suggesting that multiple willow varieties suited for similar site conditions can be used in a LSF.

A few main challenges in this study included the control of weeds and the likelihood of soil compaction on the LSF right-of-way. Controlling weeds in the first few growing seasons of LSF establishment is crucial for a successful LSF. While post-emergent herbicides were applied during the first year of LSF establishment in this study, many annual and perennial weeds still occurred at the study site, requiring many hours of hand-weeding during the first two growing seasons. Additional weed control methods, such as the application of a pre-emergent herbicide or the use of landscape fabric or mulch, would likely improve the establishment of future LSFs and reduce the need for manual labor. Additionally, rights-of-way are often compacted during road construction, which can limit LSF establishment. While compaction was not assessed on the LSF right-of-way in this study, it may have slightly stunted willow growth. Ripping the sub-soil on a right-of-way prior to planting may help improve willow LSF establishment in the future by removing any soil hardpans.

In Chapter 2, all shrub species and varieties had good establishment, and all willows outperformed the traditional LSF species, although herbicide application may have stunted traditional LSF shrubs. Willows may therefore provide LSFs that establish faster than many shrub species currently being used for LSFs. Furthermore, their high-density planting arrangements may provide narrower LSFs than many traditional LSF species while providing the same snow capture benefits. Shrub-willows are typically planted with 60 cm between plants within a row and 76 cm between rows, while many traditional LSF species are planted with 1.2 m between rows and 1.2 m between plants within a row, based on conservation planting guidelines (NRCS 2009). Thus, shrub-willow LSFs could potentially require less area on the landscape than many traditional LSF species.

Within willows, I found that the native willow, *S. petiolaris*, was comparable in establishment and growth to the highest performing willow varieties (Fish Creek and Oneonta) and may be suitable for LSFs. When selecting species or varieties for a LSF, it is important to consider the morphological characteristics of the species. Creating a LSF with a consistent optical porosity throughout the length and height of a LSF is desirable for a consistent snow trapping efficiency and downwind drift length throughout the LSF (Volk et al. 2006; Kuzovkina and Volk 2009). Variability in these factors can lead to inconsistent road protection from snow drifts. An advantage of hybrid willow varieties is that they tend to have relatively consistent optical porosity and growth for a given planting arrangement in a LSF (Ogdahl et al., in review). Native willows, especially from different genetic sources, may have more variability in these morphological characteristics. Therefore, identifying and propagating from multiple parent plants with similar morphology is recommended for creating a native willow LSF that is relatively uniform in porosity and height as well as somewhat genetically diverse for resistance and resilience to disease outbreaks or other disturbances. Future studies should evaluate the establishment, growth, and optical porosity of native willows in LSF planting arrangements.

Most willows showed no difference in response to coppice dates, but the two varieties that did (Fish Creek and S25) showed opposite responses. This may be unique to the varieties and more research is needed to explain this, but a spring coppice may be suitable for most willow LSF candidates. If a spring coppice is to be performed, it should be done as early in the spring as possible while willows are still dormant. Ultimately, the potential snow capture benefits of leaving first-year stems over the winter should be considered when deciding on a coppice date. In Chapter 1, only 2 to 4 stems were present on most plants after the first growing season, giving most varieties and planting arrangements a porosity of 95% or more (personal observation). Personal observations during the first winter also suggested the stems were providing little snow capture, as most plots were filled to capacity (snow drifts covering the willows) by the end of Feb 2014. If it appears the benefits of leaving stems over the winter will be minimal, a fall coppice may be suitable. Access to plots or a LSF in the fall will likely be easier, given the lack of melting snow drifts and thawing ground. Furthermore, a fall coppice will reduce the risk of stem damage or tearing caused by wind or blowing snow, as well as ensure no growth is lost to budding in the following spring, in case of a late coppice.

Future research efforts should continue to document willow LSF growth and porosity on the US Highway 14 right-of-way. While I was unable to assess third-year growth of the LSF due to the study timeline, visual inspection during the summer of 2015 revealed many willows had grown considerably since 2014, some with heights estimated to be around 3 to 4 m. Furthermore, this study verified a method for measuring optical porosity of LSFs, originally developed by researchers at Syracuse University in New York State. Future research should employ this method to document LSF porosity and snow storage capacity for LSFs of different species and ages throughout Minnesota to assess their effectiveness. Additionally, this research revealed that a native shrub willow (*S. petiolaris*) had comparable growth to the top performing bioenergy willow varieties at our study site. Future research should test the use of native shrub willows in LSF configurations. Given the presence of 18 native willow species in Minnesota, they may provide a suitable local plant source for future LSFs in the state.

REFERENCES

Abrahamson LP, Volk TA, Smart LB, Cameron KL (2010) Shrub willow biomass producer's handbook. State University of New York, College of Environmental Science and Forestry, Syracuse, NY

Amichev B, Hangs R, Bélanger N (2015) First-rotation yields of 30 short-rotation willow cultivars in central Saskatchewan, Canada. Bioenerg Res 8:292–306

Argus GW (1997) Infrageneric classification of *Salix* (*Salicaceae*) in the New World. Syst Bot Monogr 52, 122 pp.

Argus GW (2007) *Salix* (*Salicaceae*) distribution maps and a synopsis of their classification in North America, north of Mexico. Harv Pap Bot 12:335–368

Bergkvist P, Nordh N, Ledin S, Olsson T (1996) Plant material for short rotation forestry. In: Ledin S, Willebrand E (eds) Handbook on how to grow short rotation forests. Swedish University of Agricultural Sciences, Uppsala, pp 11.6.1–11.6.20 Department of short rotation forestry

Blanken PD (2009) Designing a living snow fence for snow drift control. Arct Antarct Alp Res 41:418–425

Boeken B, Canham CD (1995) Biotic and abiotic control of the dynamics of gray dogwood (Cornus Racemosa Lam.) shrub thickets. J Ecol 83:569–580

Brandle JR, Hodges L, Tyndall J, Sudmeyer RA (2009) Windbreak practices. In: Garrett HE (ed) North American agroforestry: an integrated science and practice, 2nd edn. Am Soc Agron, Madison, pp 75–103

Buchholz T, Volk TA (2010) Improving the profitability of willow crops—identifying opportunities with a crop budget model. Bioenerg Res 4:85–95

Cameron KD, Ballard BB, Smart LB, Abrahamson LP, Volk TA (2008) Standard Operating procedures for measurement of yield trials: version 1.1. State University of New York, College of Environmental Science and Forestry, Syracuse

Daigneault W, Betters DR (2000) A comparison of the economic efficiency of living and artificial snowfence designs for road protection. West J Appl For 15:70–74

Fay L, Shi X (2012) Environmental impacts of chemicals for snow and ice control: state of the knowledge. Water Air Soil Pollut 223:2751–2770

Gamble JD, Johnson G, Sheaffer CC, Current DA, Wyse DL (2014) Establishment and early productivity of perennial biomass alley cropping systems in Minnesota, USA. Agroforest Syst 88:75–85

Grogan P, Matthews R (2002) A modelling analysis of the potential for soil carbon sequestration under short rotation coppice willow bioenergy plantations. Soil Use Manage 18:175–183

Gullickson D, Josiah SJ, Flynn P (1999) Catching the snow with living snow fences. University of Minnesota Extension Service, St. Paul

Haβ A, Brauner O, Schulz U (2012) Diversity, distribution and abundance of honeybees (*Apis mellifera*) and wild bees (*Apidae*) on a willow short-rotation coppice. Mitt Dtsch Ges Allg Angew Entomol 18:147–151

Heavey JP (2013) Structure and function of living snow fences in New York State. Master's thesis. State University of New York College of Environmental Science and Forestry, Syracuse, NY

Heavey JP, Volk TA (2013) Coppicing living snow fences. Fact sheet series: fact sheet #8. Research Foundation for the State University of New York College of Environmental Science and Forestry, Syracuse, NY

Heavey JP, Volk TA (2014) Living snow fences show potential for large storage capacity and reduced drift length shortly after planting. Agroforest Syst 88:803–814

Isebrands JG, Aronsson P, Carlson M, Ceulemans R, Coleman M, Dickinson N, Dimitriou J, Doty S, Gardiner E, Heinsoo K, Johnson JD, Koo YB, Kort J, Kuzovkina J, Licht L, McCracken AR, McIvor I, Mertens P, Perttu K, Riddell Black D, Robinson B, Scarascia Mugnozza G, Schroeder WR, Stanturf J, Volk TA, Weih TA (2014) Environmental applications of poplars and willows. In: Isebrands JG, Richardson J (eds) Poplars and willows: trees for society and the environment. The Food and Agriculture Organization of the United Nations and CABI, Rome, pp 258–336

Keoleian GA, Volk TA (2005) Renewable energy from willow biomass crops: life cycle energy, environmental and economic performance. Crit Rev Plant Sci 24:385–406

Kuzovkina YA, Quigley MF (2005) Willows beyond wetlands: uses of *Salix* L. species for environmental projects. Water Air Soil Pollut 162:183–204

Kuzovkina YA, Volk TA (2009) The characterization of willow (*Salix* L.) varieties for use in ecological engineering applications: co-ordination of structure, function and autecology. Ecol Eng 35:1178–1189

Labrecque M, Teodorescu TI, Daigle S (1997) Biomass productivity and wood energy of *Salix* species after 2 years growth in SRIC fertilized with wastewater sludge. Biomass Bioenerg 12:409–417

McCracken AR, Dawson WM, Bowden G (2001) Yield responses of willow (*Salix*) grown in mixtures in short rotation coppice (SRC). Biomass Bioenerg 21:311–319

MnDOT Minnesota Department of Transportation (2015) Bare lane detail for US 14: Janesville to Waseca, November 2014–March 2015. Waseca Truck Station, Maintenance Area 7.

Mundt CC (2002) Use of multiline cultivars and cultivar mixtures for disease management. Annu Rev Phytopathol 40:381–410

NCDC National Climatic Data Center (2015) 1981–2010 climate normals. National Oceanic Atmospheric Administration. http://www.ncdc.noaa.gov/. Accessed 17 Mar 2015

NRCS Natural Resources Conservation Service (2009) Code 380: conservation practice standard for windbreak/shelterbelt establishment. NRCS-Minnesota Field Office Technical Guide.

Pinheiro JC, Bates DM (2000) Mixed effects models in S and S-plus. Springer, New York

Ogdahl E, Zamora D, Johnson G, Wyatt G, Current D, Gullickson D (in review) Establishment and potential snow storage capacity of willow (Salix spp.) living snow fences in south-central Minnesota, USA. Agroforest Syst

Powell K, Reed C, Lanning L, Perko D (1992) The use of trees and shrubs for control of blowing snow in select locations along Wyoming highways. Federal Highway Administration Report No. FHWA-92-WY-001

Rowe RL, Hanley ME, Goulson D, Clarke DJ, Doncaster CP, Taylor G (2011) Potential benefits of commercial willow short rotation Coppice (SRC) for farm-scale plant and invertebrate communities in the agri-environment. Biomass Bionenerg 35:325–336

Shaw DL (1988) The design and use of living snow fences in North America. Agric Ecosyst Environ 22:351–362

Shulski MD, Seeley MW (2001) Climatological characterization of snowfall and snow drift in Minnesota: for the design of living snow fences. Minnesota Department of Transportation Agreement 74708. University of Minnesota, Minneapolis

Shulski MD, Seeley MW (2004) Application of snowfall and wind statistics to snow transport modeling for snowdrift control in Minnesota. J Appl Meteorology 43:1711–1721

Smith WR (2008) Trees and shrubs of Minnesota. Minnesota Department of Natural Resources, University of Minnesota Press, Minneapolis

Souch CA, Martin PJ, Stephens W, Spoor G (2004) Effects of soil compaction and mechanical damage at harvest on growth and biomass production of short rotation coppice willow. Plant Soil 263:173–182

SROC Southern Research and Outreach Center (2015) Monthly weather reports. http://sroc.cfans.umn.edu/WeatherInformation/DailyWeather/index.htm. Accessed 7 Aug 2015

St-Pierre RG, Zatylny AM, Tulloch HP (2005) Evaluation of growth, yield, and fruit size of chokecherry, pincherry, highbush cranberry, and black currant cultivars in Saskatchewan. Can J Plant Sci 85:659–664

Sturges DL (1983) Shelterbelt establishment and growth at a windswept Wyoming rangeland site. USDA Forest Service, General Technical Report RM-243. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. pp. 12

Tabler RD (1980) Geometry and density of drifts formed by snow fences. J Glaciol 26:405–419

Tabler RD (1997) Recommended drift control measures for selected sites in southern Minnesota: final report. Minnesota Department of Transportation Agreement No. 75966. Tabler and Associates, Niwot

Tabler RD (2003) Controlling blowing and drifting snow with snow fences and road designs. National Cooperative Highway Research Program Project 20-7(147) Tabler and Associates, Niwot

Tabler RD, Meena JA (2006) Effects of snow fences on crashes and road closures: a 34 year study on Wyoming interstate-80. Cold Reg Eng 2006:1–10

Thelemann R, Johnson G, Sheaffer C, et al (2010) The effect of landscape position on biomass crop yield. Agronomy Journal 102:513–522

USDA United States Department of Agriculture (2011) Living snow fence: an agroforestry practice. USDA National Agroforestry Centre, Lincoln

Volk TA, Verwijst T, Tharakan PJ, Abrahamson LP, White EH (2004) Growing fuel: a sustainability assessment of willow biomass crops. Front Ecol Environ 2:411–418

Volk TA, Abrahamson LP, Nowak CA, et al (2006) The development of short-rotation willow in the northeastern United States for bioenergy and bioproducts, agroforestry and phytoremediation. Biomass Bionenerg 30:715–727

Wyatt G, Zamora D, Smith D, Schroder S, Paudel D, Knight J, Kilberg D, Current D, Gullickson D, Taff S (2012) Economic and environmental costs and benefits of living snow fences: safety, mobility, and transportation authority benefits, farmer costs, and carbon impacts. Minnesota Department of Transportation Research Services, Final Report 2012-13

Zamora DS, Apostol KG, Wyatt GJ (2014) Biomass production and potential ethanol yields of shrub willow hybrids and native willow accessions after a single 3-year harvest cycle on marginal lands in central Minnesota, USA. Agroforest Syst 88:593–606

Zamora DS, Apostol KG, Berguson WE, Volk TA, Wright J, Ogdahl EJ (2015) Short rotation woody crops biomass production. In: Jose S, Bhaskar T (eds) Biomass and biofuels: advanced biorefineries for sustainable production and distribution. CRC Press, Taylor & Francis Group, Boca Raton, FL

Zan CS, Fyles JW, Girouard P, Samson RA (2001) Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec. Agric Ecosyst Environ 86:135–144

Appendix A

Snow Climatological Models for Waseca, Minnesota

The effectiveness of a snow fence can ultimately be determined by its potential snow storage capacity relative to the mean annual snow transport for the region in which the snow fence is located (Heavey and Volk 2014). The mean annual snow transport for a specific region is delimited by the snow accumulation season (SAS) of the region. The SAS is the period of drift growth during an average winter. It starts when the average daily temperature falls below freezing and ends when the average daily temperature exceeds 0^{o}C. Although blowing snow can occur outside of this range, it typically melts soon thereafter and does not usually contribute significantly to drift growth. Tabler (2003, p. 95) developed an algorithm to define the SAS, based on thirty-year monthly temperature normals, as follows:

$$n = 30T_{+}/(T_{+} - T_{-}) \tag{1}$$

where n is the number of days between the middle of the last above-freezing month and first 0^{o}C date in the fall, or the last 0^{o}C date and the middle of the first above-freezing month in the spring. T_{+} and T_{-} are then the mean temperatures of the warmer month and the 0^{o}C month, respectively, for either fall or spring. The onset date of the SAS in autumn is determined by adding n, as calculated for the fall, to the mid-date of the warmer month for which T_{+} was used, whereas the end date in the spring is determined by subtracting n, as calculated for the spring, from the mid-date of the first above-freezing month in the spring. For Waseca, thirty-year monthly normals (1981-2010) were obtained for SROC from the National Climatic Data Center (National Oceanic and Atmospheric

Administration, http://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/climate-normals, accessed 17 Mar 2015) (Table A-1). The SAS for Waseca was determined using Equation (1).

Table A-1 Selected thirty-year normals (1981-2010) for the Southern Research and Outreach Center in Waseca, MN.

	Nov	Dec	Jan	Feb	Mar	Apr
^{o}F	32.7	17.8	13.2	18.5	31.2	46.1
^{o}C	0.4	-7.9	-10.4	-7.5	-0.4	7.8
Precip (in.)	2.2	1.5	1.3	1.0	2.5	3.2
Precip (cm)	5.5	3.8	3.2	2.5	6.3	8.2
Snowfall (in.)	7.8	13	9.5	9	10.2	2.7
Snowfall (cm)	19.8	33.0	24.1	22.9	25.9	6.9

Data obtained from the National Climatic Data Center, NOAA

The prevailing direction of snow transport is another essential component in determining the mean annual snow transport and thus snow fence effectiveness. The prevailing direction of snow transport for Waseca was determined through both modeling and field measurements. Tabler (2003) described wind-defined snow transport as the potential snow transport from all wind directions and wind speed classes for a region, assuming an unlimited fetch distance and snow supply. This is summarized as Qupot in the following equation (Tabler 2003):

$$\text{Qupot} = (u_{i,f}^{3.8}/233{,}847)(f_{i,j})(86{,}400)(n) \qquad (2)$$

where u_i is the midpoint of the ith wind-speed class at a height of 10 m, f is frequency of observations for the given u_i and n is the number of days in a specific month or SAS of a region. In the above equation, 10-m wind speed is adjusted by the denominator to represent snow transport in the first 0-5 m above the ground, where snow transport is most common (Tabler 2003).

To determine Qupot for Waseca, wind direction and speed data, recorded 3 times per hour to the nearest 10^o, were obtained over 5 SAS, beginning 16 Nov 2010 and ending 17 Mar 2015, from the Waseca Municipal Airport (44.0733^o N, 93.5531^o W). The airport is approximately 3.1 km (1.9 mi) from the living snow fence study and is an Automated Surface Observing System (ASOS), which utilizes standardized wind instrumentation mounted at a height of 10 m (Shulski and Seeley 2004). Five SAS were assumed to be an adequate representation on wind speed and direction based on previous assessments (Shulski and Seeley 2004, Tabler 1997, p. 19). Wind speed and direction frequencies were determined in WRPLOT View 7.0 software by Lakes Environmental, using wind speed classes of 5 knots (2.6 m/s) and the 16 cardinal directions, following Tabler (1997, p. 19). Frequencies (Table A-2) were calculated for all directions of wind speed classes greater than or equal to 13 knots (7 m/s), as this is the mean wind speed threshold for blowing snow in Minnesota (Shulski and Seeley 2004). Qupot was determined by summing Qupot, from Eq. (2), for all wind classes and frequencies (Table A-3).

Table A-2 Waseca wind speed frequencies (%) by class (kts) and direction for snow accumulation season dates, 2010 to 2015.

Direction	13 - 17	28 - 22	23 - 27	28 - 32	33 - 37	>37
N	0.558	0.208	0.002	0.000	0.000	0.000
NNE	0.369	0.105	0.002	0.000	0.000	0.000
NE	0.137	0.024	0.000	0.000	0.000	0.000
ENE	0.149	0.024	0.002	0.000	0.000	0.000
E	0.271	0.053	0.000	0.000	0.000	0.000
ESE	0.491	0.077	0.012	0.000	0.000	0.000
SE	1.495	0.333	0.022	0.000	0.000	0.000
SSE	1.526	0.297	0.007	0.000	0.000	0.000
S	2.590	0.764	0.053	0.005	0.000	0.000
SSW	1.090	0.513	0.041	0.007	0.000	0.000
SW	0.434	0.110	0.017	0.000	0.000	0.000
WSW	0.302	0.153	0.050	0.005	0.000	0.000
WSW	1.826	0.633	0.089	0.014	0.002	0.000
WNW	3.654	2.180	0.558	0.105	0.014	0.000
NW	2.101	1.095	0.127	0.012	0.000	0.000
NNW	1.450	0.470	0.034	0.000	0.000	0.000

Frequencies (%) of wind speeds equal to or greater than 7 m s^{-1} as proportion of all wind speed observations

Table A-3 Waseca wind-defined potential snow transport, Qupot (kg m^{-1}), by class (kts) direction for snow accumulation season dates, 2010 to 2015

Direction	13 - 17	28 - 22	23 - 27	28 - 32	33 - 37	>37
N	593	661	18	0	0	0
NNE	392	334	18	0	0	0
NE	145	76	0	0	0	0
ENE	158	76	18	0	0	0
E	288	167	0	0	0	0
ESE	522	243	89	0	0	0
SE	1589	1056	160	0	0	0
SSE	1622	942	53	0	0	0
S	2752	2423	390	71	0	0
SSW	1158	1626	302	106	0	0
SW	461	349	124	0	0	0
WSW	321	486	372	71	0	0
WSW	1940	2005	656	213	60	0
WNW	3882	6912	4132	1560	362	0
NW	2233	3471	940	177	0	0
NNW	1540	1489	248	0	0	0

The prevailing wind direction was determined by summing the product of the midpoint azimuth of each cardinal direction and the total Qupot for each direction and dividing the sum by the total Qupot for all directions and wind speed classes (Tabler 2003, p. 100). Field observations on snow transport direction were taken over the 2013-2014 and 2014-2015 SAS dates. These were recorded by orienting a compass with streamlined drift contours downwind of right-of-way posts along the snow fence site (Figure A-1). This method provides an average direction of drifting and thus the prevailing direction of snow transport for the area (Tabler 2003, p. 85).

Figure A-1 Field-based method for determining direction of prevailing snow transport by measuring streamlined snowdrift orientation using a compass.

The prevailing direction of snow transport from model estimates and field observations were used to orient the fetch distance for the snow fence site. The fetch distance is the contributing distance of snow transport in m, typically defined as the upwind distance from the snow fence to the nearest identifiable wind obstruction, such as a road ditch, perennial vegetation, or a homestead. Fetch distance was calculated in a GIS by orienting fetch length measurements for each plot in the snow fence to the approximate prevailing snow transport direction. These measurements were then averaged to obtain a single fetch value for use in the mean annual snow transport model.

The mean annual snow transport model was developed by Tabler (2003) to estimate a region's average amount of snow transported by wind over the snow accumulation season. This is estimated by the following equation:

$$Q = 1500\theta S_{\mathrm{we}}(1\text{-}0.14^{F/T}) \tag{3}$$

where θ is the relocation coefficient, or fraction of snowfall relocated by the wind; S_{we} is the snowfall water equivalent in m; F is the fetch distance in m; and T is the maximum fetch distance, equal to 3000 m. S_{we} was determined by multiplying the mean snowfall over the SAS by the average snow water equivalent. The relocation coefficient and mean snow water equivalent were determined via algorithms developed by Shulski and Seeley (2004) on blowing snow properties for Minnesota. These values are based on interpolations of historical wind and snow data for over 180 weather stations throughout Minnesota. The fetch distance was equal to the average measured fetch distance for the snow fence site.

After determining mean annual snow transport, the final objective is to determine the amount of annual transport trapped by the snow fence. This is done through determining the snow fence's snow storage capacity. The ratio of snow storage capacity to mean annual transport indicates a snow fence's effectiveness; if the ratio is equal to or greater than 1, the snow fence is storing all of the mean annual snow transport (Heavey and Volk 2014).

Snow storage capacity is related to the height and porosity, or amount of open space, in the snow fence. Tabler (2003) described this relationship in the following model:

$$Q_c = (3 + 4P + 44P^2 - 60P^3)H^{2.2} \qquad (4)$$

where P is the porosity (as a decimal) and H is height in m. Both values can be obtained through field measurements. For height in the model, height measurements were taken from the plant growth measurements and averaged by treatment. Porosity was measured with the chroma-key technique (adopted from Heavey and Volk 2014) in early winter 2014 (19 Dec 2014), after the majority of shrubs had dropped their leaves. Measurements were taken at 4 equidistantly spaced points in each plot, starting at approximately 3.7 m (12 ft) from the end of each plot. At each point, a 1 m wide by 3 m tall red backdrop was placed behind the fence and photographed with a Canon PowerShot A540. Photographs were taken at a consistent height above the ground at approximately 3.3 m from the front of each fence point to capture the entire backdrop. Photographs were then processed in Adobe Photoshop by removing the area outside of the backdrop, leaving only the backdrop and the vegetation in front of it. To obtain porosity values, the number of backdrop pixels were counted and divided by the total number of pixels in the entire cropped area and multiplied by 100. Porosity values were averaged by treatment for use in Equation (4). Equation (4) was used to estimate snow storage capacity for each treatment. The ratio Q_c:Q was used to gauge snow fence effectiveness.