

New York State Department of Transportation Research Project C-06-09

Designing, Developing and Implementing a Living Snow Fence Program for New York State

Final Report

July 2015



Conducted for the New York State Department of Transportation by the
State University of New York College of Environmental Science and Forestry
Department of Forest and Natural Resources Management
1 Forestry Drive
Syracuse, NY 13210

Authors:
Justin P. Heavey, Timothy A. Volk, Lawrence P. Abrahamson,
Phillip Castellano and Ruth Williamson



State University of New York
College of Environmental Science and Forestry

DISCLAIMER

This report was funded in part through grant(s) from the Federal Highway Administration, United States Department of Transportation, under the State Planning and Research Program, Section 505 of Title 23, U.S. Code. The contents of this report do not necessarily reflect the official views or policy of the United States Department of Transportation, the Federal Highway Administration or the New York State Department of Transportation. This report does not constitute a standard, specification, regulation, product endorsement, or an endorsement of manufacturers.

Acknowledgements

This study was funded by the New York State Department of Transportation (NYSDOT) and by the Federal Highway Administration (FHWA). The project was administered through the Region 2 University Transportation Research Center (UTRC) at the City University of New York under the direction of Dr. Camille Kamga of UTRC. John Rowen from NYSDOT served as the NYSDOT Project Manager. Timothy A. Volk, of the State University of New York's College of Environmental Science and Forestry (SUNY-ESF), was the Principal Investigator. Lawrence P. Abrahamson, Justin P. Heavey, Phillip Castellano and Ruth Williamson of SUNY-ESF were co-Principal Investigators. Helpful input and contributions to the project were provided by the Technical Working Group and other NYSDOT staff, including: Tim Baker, Darrell Kaminski, Peter Morelock, Jim Merritt, Lubov Koptsev, Mike Lashmet, Joe Doherty, Deborah Mooney, Thelma Rasheed and Denise Bumbulsky. Rosalind Weber and Mike Kowalczyk represented FHWA during this research. This work included four classes in NYSDOT regions, where nearly 110 NYSDOT and people from other transportation and government organizations designed and planted living snow fences. Thanks to Ray Oram, Dave Tackley and James Buck in NYSDOT Regions 2, 5 and 9 for serving as regional contacts for starting and presenting the training. Thanks to the staffs at the following Residencies: Onondaga East; Erie South, Delaware South; and Oneida East. Of the four classes, three designed and planted living snow fences on NYSDOT right of way. In Delaware Residency South, NYSDOT wishes to acknowledge the Delaware County Soil and Water Conservation District for assistance in planning and hosting the design class and the New York City Department of Environmental Protection, Downsview Office for providing the site where the living snow fence was planted. SUNY-ESF would like to thank project staff Bernardo Latorre Monteagudo and Eric Fabio, and the numerous undergraduate and graduate student research staff who assisted in the installation, maintenance, monitoring and analysis of the willow living snow fences. SUNY-ESF would also like to thank all the NYSDOT staff who participated in the classes and provided on-the-ground support for fence installation, maintenance and monitoring. NYSDOT and SUNY-ESF would also like to acknowledge the late Ronald Tabler for his work on structural and living snow fences, which provided much of the basis for this study.

1. Report No. C-06-09	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Designing, Developing and Implementing a Living Snow Fence Program for New York State		5. Report Date July 2015	
		6. Performing Organization Code	
7. Author(s) Justin P. Heavey, Timothy A. Volk, Lawrence P. Abrahamson, Phillip Castellano, Ruth Williams		8. Performing Organization Report No.	
9. Performing Organization Name and Address State University of New York College of Environmental Science and Forestry		10. Work Unit No.	
		11. Contract or Grant No.	
12. Sponsoring Agency Name and Address NYS Department of Transportation 50 Wolf Road Albany, New York 12232		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes Project funded in part with funds from the Federal Highway Administration.			
16. Abstract: Living snow fences (LSF) are a form of passive snow control designed to mitigate blowing and drifting snow problems on roadways. Blowing and drifting snow can increase the cost of highway maintenance and create hazardous driving conditions when snow is lifted off the ground by wind and transported toward a road. LSF disrupt wind patterns, causing blowing snow to be deposited in designated areas around the fence and away from the road. LSF are rows of vegetation (trees, shrubs, corn) that perform the same function as structural (wooden, plastic) snow fences with potentially longer life cycles and better returns on investment. This project provided a literature review; training materials; classroom and field workshops on LSF design, installation and maintenance; four demonstration sites with installed LSF; protocols for the assessment of sites and operational fences; a study of 18 LSF using these protocols; the identification of key factors for successful LSF in NY State and beyond; and a benefit-cost tool. Key research outcomes include improved understanding of snow trapping function as LSF grow over time and improved design recommendations based on these findings. Applying these design standards along with best practices for installation and maintenance developed in this project can increase the feasibility and effectiveness of LSF. Well designed and managed LSF can produce numerous economic, safety and environmental benefits to transportation agencies and the public.			
17. Key Words living snow fences, snow and ice, passive snow control, willow snow fences, technology transfer		18. Distribution Statement No restrictions	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 456	22. Price

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Executive Summary

Living snow fences (LSF) are a form of passive snow control designed to mitigate blowing and drifting snow problems on roadways. Blowing and drifting snow can increase the cost of highway maintenance and create hazardous driving conditions when snow is lifted off the ground by wind and transported toward a road without disruption. LSF disrupt wind patterns, causing blowing snow to be deposited in drifts in designated areas around the fence and away from the road. LSF are rows of vegetation (trees, shrubs, standing corn rows) that perform the same function as structural (wooden, plastic, metal) snow fences with potentially longer life cycles and better returns on investment.

This project provided technology transfer for LSF through the creation and dissemination of training materials, and combined classroom and field training workshops on LSF design and installation/maintenance held at four New York State Department of Transportation (NYSDOT) residencies around the state. Four willow LSF were installed at known blowing snow problem areas as part of the training workshops. Protocols to assess potential sites and operational LSF were created and applied to the four demonstration sites. These protocols were further applied in an original research study that measured structural characteristics and snow trapping potential of 18 LSF of various ages and vegetation types in locations across New York State.

Based on the literature review conducted at the start of this project, this new research is the most comprehensive study on LSF to date and provides new understanding on the structure and snow trapping potential of LSF over time. Study findings identified key factors for successful LSF that have important implications related to the design, feasibility and effectiveness of LSF. This new information has been incorporated into LSF guidelines and protocols during the course of this project. A benefit-cost tool for LSF was also created, tested and revised as part of this project. Example scenarios modeled using the tool have shown that willow LSF and LSF of other vegetation types can have positive net present values and other metrics of financial analysis by reducing snow and ice control costs. The benefit-cost tool also demonstrated that LSF can produce large amounts of other public benefits (that can be quantified in economic values) such as reduced accidents rates and avoidance of reduced travel speeds. LSF can also provide environmental benefits that increase the sustainability of transportation projects consistent with the standards of the NYSDOT GreenLITES environmental certification program.

Introduction

LSF have been used for decades or longer to prevent blowing snow problems on roads around the world, as well as to protect other areas such as railroad tracks or houses. Blowing snow problems typically occur next to large open areas where no or limited obstructions to blowing snow exist, such as agricultural fields that have been cleared of vegetation or large frozen lakes. In New York, blowing and drifting snow problems occur most frequently around large open agricultural fields adjacent to roadways with little or no vegetation or other obstructions between the road and field. Blowing and drifting problems often occur in remote rural locations and can create the need for frequent plowing, salting, de-icing, snow blowing and other methods of snow and ice control. These problems can occur consistently and repeatedly in problem areas as the wind continues to blow and transport snow for days or even

weeks after a snow event. This often requires frequent and costly trips to remote locations and sometimes leads to road closures, automobile accidents and other severe situations.

LSF are planted in such areas to mitigate these situations by acting as an obstruction to the wind and blowing snow. This disruption of blowing snow creates wind turbulence and eddies (swirling winds) around fence, causing blowing snow to be deposited in drifts on both the upwind and downwind side of the fence, away from the road.

LSF have been used for decades in New York and are considered a best practice. But previous research on LSF is limited and design standards have been loosely adapted from structural snow fences. LSF and structural snow fences trap snow in the same manner and produce essentially the same result, with one important (but often overlooked) difference. LSF grow over time, which changes the fence's snow holding capacity and snow drift shape as plants mature. This critical factor has not been fully accounted for in previous research studies and has not been incorporated into LSF design protocols and educational publications. Several NYSDOT residencies have engaged in LSF to various degrees before this project started, with varying degrees of success. In the early 2000's, workshops were held in NYSDOT Region 5 and facilitated by the late Ronald Tabler, whose work continues to be the most extensive engineering study and design standards for structural snow fences and provides important insights into LSF. An engineering design tool for LSF --"Snowman" (Snow management) -- was created by NYSDOT and researchers from these workshops, but the use and functionality of this tool for LSF design has been limited. Tabler focused on structural snow fences. The nuances of his work on LSF are often not transferred correctly into simplified LSF protocols or educational publications. One of the main areas where this is most evident - and related to the changing nature of LSF over time - is lack of emphasis in the literature on the potential for excess storage capacity of mature LSF and the impact excess storage capacity can have on downwind drift length.

When LSF snow trapping capacity (driven by height growth over time) exceeds the annual quantity of blowing snow at a site, the length of the downwind drift is reduced, or does not reach the maximum possible drift length during the snow season. Estimating when this reduced drift length will occur in the life cycle of LSF and consequently how much drift length will be reduced is of critical importance when designing LSF in regards to the chosen setback distance, or distance between fence and the road.

Not accounting for excess storage capacity of large, mature LSF and using the standard design assumption for structural snow fences of setback distance being set equal to 35H (or 35 times the height of the fence) will generally result in setbacks that are far larger than necessary. This excessive setback distance can lead to "near-snow problems" of blowing snow between the fence and the road, or the inability to install LSF beyond the right of way boundary on privately held land, limiting the effectiveness and feasibility of LSF. Also critically important to the success of LSF is the use of best practices for site assessment, design, installation and maintenance. These and other issues related to the structure, function, analysis and design of LSF are addressed in this study and have been incorporated into training materials, workshops, and protocols.

Research Method

Training materials, including a series of seven fact sheets and two PowerPoint presentations, were prepared to assist in the design and installation classes. Training materials were created from an extensive literature review of LSF, previous research and development efforts conducted by SUNY-ESF, and improved methods and protocols developed in this project. Five classes were held during the project. The first four classes were held at four different NYSDOT residencies in Onondaga, Erie, Delaware and Oneida Counties. Each class had two sessions.

In the first session, generally held in the fall, participants learned about basics of blowing snow problems, addressing problems with LSF, site assessment and fence design. In the field component of the fall session, students visited a site identified by residency staff as having a blowing snow problem and addressing the factors for site assessment as a group, including talking through potential challenges to fence installation and possible solutions.

The following spring, the class reconvened for a one- or two-day long session. The classroom aspect of the spring session covered LSF design, installation, maintenance and best practices. In the field component of the second session, participants observed and assisted in site preparation and installation of a living snow fence on the site. Shrub willow LSF were used in the field sessions, as this vegetation type is recognized as a best practice for LSF due to the rapid growth rate of willow, the ease of propagation from dormant stem cuttings, tolerance of high planting density, consistent porosity, etc. Protocols to assess and measure LSF sites were developed and applied at each site and these methods and findings were presented and applied in each of the classes as part of the comprehensive demonstrations of site identification, analysis, design, installation and maintenance of LSF. Methods of site assessment included using geographic information systems (GIS) to assess and measure the site, soil sampling and interpretation of results, assessing vegetation and land use history, assessing the blowing snow problem, developing strategies to overcome site challenges (ditches, trees, utilities), etc.

The fifth and final class was planned to be a winter workshop to observe and discuss functional LSF in the landscape. Scheduling of this tour so participants from multiple residencies across the state could participate proved difficult amongst competing and uncertain demands on NYSDOT staff for snow and ice control during the winter. A summer class to observe mature LSF was held instead to accommodate previous participants from various residences attending. The workshop, held in NYSDOT Region 2, consisted of a brief classroom training in the morning, followed by site visits to four LSF in Region 2 of various ages and vegetation types including willow, evergreen trees and shrubs. Instruction and discussion at each stop focused on the original research conducted as part of this project and how the dynamics of maturing LSF affect snow trapping function over time. This dynamic was illustrated by visiting LSF with a range of ages, plant types, heights and snow storage capacities and explaining how these factors affected the length of the downwind drift and selection of setback distance and other design factors.

Protocols in this project were developed to measure and evaluate LSF based on work by Ronald Tabler and previous efforts by the Willow Project Research Group at SUNY-ESF. These protocols included methods for taking accurate measurements and developing sampling

designs to evaluate key vegetation characteristics of plant height and optical porosity, as well as gathering other information on site characteristics using GIS. These protocols were applied to a comprehensive study of 18 living snow fences of various vegetation types and ages across the state. Data on plant characteristics were used to model snow trapping capacity of the fences and downwind drift length based on the engineering equations of Ronald Tabler. The range of ages from three to eleven years after planting allowed plant height, porosity and the resulting snow storage capacity and down drift length to be modeled over time.

The benefit-cost tool for this project was created by itemizing costs associated with LSF installation and maintenance, and the machinery/logistics of snow and ice control by NYSDOT. Other variables were included in the model based on transportation industry standards to quantify benefits from LSF related to value travel time savings (VTTS) and accident reduction factor (ARF). The model was presented to NYSDOT staff via a webinar and improvements were made to the model based on comments and discussions from the project's technical working group.

Findings and Conclusions

Nearly 110 people attended the classes. NYSDOT staff who attended were a diverse group from all parts of the agency, including Highway Maintenance Workers, Landscape Architects, engineers and environmental specialists. Students also included staff from the New York State Thruway Authority and local governments. Class instructors, content and format received high evaluations from students.

Several students have since applied this training to LSF projects in their home region. The training materials developed are comprehensive and cover every aspect of LSF from site assessment through maintenance of installed fences. These training materials include best practice guidelines for site assessment, design, installation and maintenance that will improve the chance of survival, growth rates, functionality and returns on investment for LSF implemented using these guidelines. The benefit-cost tool created is user friendly and customizable to NYSDOT operations and a variety of installation and maintenance variables for LSF. All of these materials are available for download in convenient fashion on the SUNY-ESF hosted website which will remain active indefinitely. A recent assessment of website traffic using Google analytics showed that this site is being accessed at rate of approximately 500 – 600 times per year.

This study found that LSF of various vegetation types can create snow trapping potential equal to the annual quantity of blowing snow at an average site in NYS as early as three years after planting, much earlier than the seven to twenty years or longer often described in the literature. Related to this, as LSF grow and increase in height, they continue to add snow storage capacity. As fence snow storage capacity continues to exceed the quantity of blowing snow at the site by larger and larger amounts, this reduces the length of the downwind drift that forms around the fence during the snow season.

These findings show LSF can be effective much sooner than previously assumed and can be safely situated nearer the road than previously assumed, due to reduced setback requirements resulting from reduced drift lengths caused by large storage snow capacity. Applying these design standards along with installation and maintenance best practices

developed in this project can increase LSF feasibility and effectiveness. Well designed and managed LSF yield economic, safety and environmental benefits to transportation agencies and the public.

Many areas of potential future research exist around LSF. A comprehensive study of LSF snow drift formations, comparing predicted values of snow load and drift shape to observed values in the field throughout single and across multiple snow seasons and fences, would further inform the LSF design and functionality. Case studies of specific locations with snow problems before and after LSF installations, including documented reductions in road maintenance costs and accident rates, would improve understanding of the financial returns on investment and offer the opportunity to apply and improve the benefit-cost tool created in this study. Additional research could be conducted to further quantify LSF's environmental benefits and their application the NYSDOT's GreenLITES program for environmental sustainability and multiple benefits including the production of renewable woody biomass, erosion control and other environmental services. LSF best practices can continue to be improved and evaluated in more detail, examining the tradeoffs of implementing certain practices at higher or lower initial costs versus long term impacts. The 18 LSF identified and evaluated in this study could be studied in more detail and could also be expanded to include a broader range of sites, vegetation types and fence ages. Other efforts could focus on statewide initiatives such as cataloging and prioritizing blowing snow problem areas and documenting the effectiveness of existing LSF. More decision analysis tools can be developed including online LSF design tools and benefit-cost modules such as those being developed in other states. More advanced studies of snow hydrology around LSF could be conducted in the field and in aerodynamic simulations in order to refine site and fence design standards. Additional development of support systems for the adoption of LSF could also be developed such as more comprehensive outreach programs for working with landowners to adopt LSF.

Statement on Implementation

Much of this project was focused on training and technology transfer. With the training, the intention was that class participants could use the protocols and best practices developed and disseminated to address blowing snow problems in various locations around the state. The technology transfer included consultations with NYSDOT staff outside the training and overview presentations to groups such as the Cornell Local Roads program.

While training helped participants better understand LSF, it appears that only participants who engaged in multiple trainings or had prior awareness of or experience with LSF were comfortable enough to implement these ideas. Providing ongoing support for LSF design and installation could encourage wider use of LSF across the state. There is no comprehensive living snow fence program within NYSDOT however, so tracking and supporting these projects on a statewide level will be challenging, but would be useful to continue advancing the technology and implementation. LSF, especially willow LSF are now a well-developed technology but there is still room to improve these systems and increase awareness about the benefits they produce. With training materials now completed, numerous LSF around the state identified and studied, and these results fed back into development of best practices and design standards, future projects will have a much stronger foundation to build upon to advance LSF science and implementation even further.

Task 1-A: Literature Review

Task 1-A: Literature Review of Living Snow Fences

Overview: Task 1-A, of the research project "Designing, Developing, and Implementing a Living Snow Fence Program for New York State", has three parts.

- Part 1 is a summary of a review of literature relevant to living snow fence.
- Part 2 is a summary of interviews conducted with staff in other state, provincial and local governments in North American that are undertaking or have undertaken living snow fence programs.
- Part 3 is a matrix of species and their relevant plant characteristics that are suitable for living snow fence plantings in New York State.

Review of Literature on Living Snow Fences

Compiled by Ruth Williamson and Timothy A. Volk

SUNY – ESF
Syracuse, NY 13210

This report is Task 1-A of the New York State Department of Transportation Research Project C-06-09 “Designing, Developing, and Implementing a Living Snow Fence Program for New York State” (PIN R021.13.881, Research Consortium Contract: No. C030506)



November 2010



State University of New York
College of Environmental Science and Forestry

Review of literature relevant to living snow fence Background on Living Snow Fences In areas where snowfall is prevalent, which includes most of New York State, snow blowing across open fields can create dangerous road conditions for the public, increase the number of accidents and injuries, and create expensive, time consuming and challenging situations for road crews to ameliorate. Snow and ice removal costs in the U.S. exceed \$2 billion each year, while indirect costs related to corrosion and environmental impacts have been estimated to add another \$5 billion each year. Factoring in costs associated with accidents and injuries would further increase this figure (Tabler 2003).

The threshold wind speed at which snow will begin to move is around 10 mph and the workability of wind speed is proportional to the cube of the wind speed (Tabler 2003), so slight reductions in wind speed can have significant impacts on snow movement and distribution. Structural or LSF have been used for a long time to reduce wind speeds and control blowing and drifting snow along roadways and other key locations. Structural snow fences that have been used include solid wood “Wyoming” snow fences, slatted wood, porous plastic, and most recently three dimensional structures like “snow snakes”. Structural snow fences can reduce blowing and drifting snow immediately after they are installed and are an effective choice in some situations, but they have a number of limitations. They have high establishment and maintenance costs because they are usually erected and removed each year, have to be stored, and have a limited useful life. In addition, a typical 4-foot high structural snow fence can quickly become buried in drifting snow, making them ineffective for the remainder of the winter.

An alternative approach to controlling blowing and drifting snow, as well as providing additional benefits to landowners and the environment, is to design and install living snow fences. These are plantings of trees, shrubs, or native grasses a short distance upwind of roads, homes, farmsteads, communities, or other important facilities (Gullickson et al. 1999). LSF can be cheaper to install and maintain than structural snow fences, have a greater height, and, therefore, can capture more snow. LSF are more aesthetically pleasing, and they have the potential to provide benefits such as wildlife habitat, CO₂ capture, and woody biomass for renewable energy. While LSF have many positive attributes, they also have limitations and are often misunderstood. Much of the previous work on LSF has been done using slow-growing species that require two or more widely-spaced rows for effective control and take 6 to 20 years to become effective (Tabler 2003, Gullickson 1999). These designs for LSF require large areas, which is a significant limitation in the northeastern United States where roadside rights-of-way are usually narrow and landowners are less willing to set aside wide strips of land. There are several options available to overcome these limitations, including the use of a single or closely-spaced double row of fast-growing willow

or other shrubs. Another approach that has been effective is to pay landowners to leave rows of standing corn in fields in years when it is grown in problem areas.

An appealing attribute of LSF is that they are made up of living plants, and if properly installed, they will be in place and function for decades. However, because they are living plants, they require more planning and care during installation to be successful compared to structural snow fences. Planning should include an assessment of the following factors:

- Blowing snow conditions at the problem area
- Determination of the best location and orientation
- Evaluation of growing conditions for plants
- Selection of the right plant material, and
- Proper site preparation for planting.

In addition, the concerns of landowners need to be addressed, since most LSF in the northeast are installed off the right-of-way. The different steps in the design and installation of LSF are often a barrier to their use because they initially appear complex, but once key principles are understood, many of these steps are easily implemented. The most important characteristics for effective LSF are high density of stems and branches during the winter, good height growth, relatively uniform density along the length of the plant, and an upright form. Many willows and other shrubs inherently possess several of these characteristics. Other plants can be used by selecting the right varieties, alone, or in combination, and using different management practices. For example, the density of willow snow fences can be varied by changing the spacing between plants, by coppicing to alter the number of stems and degree of side branching, and by varying the number of rows planted. Rates of establishment can be modified by changing the size of planting stock, correctly matching plant species to site conditions, which can often be quite harsh, and altering soil conditions and snow fence management techniques.

Despite the increased attention and application that LSF have received in other parts of the U.S., they are not widely used in the Northeast. This is due to a lack of knowledge about them among landowners and highway managers, lack of demonstration sites, limited data illustrating their impact and benefits, and hesitation among landowners to plant permanent strips to woody plants in their fields. However, there is an extensive amount of literature that is available on both structural and living snow fences.

Part 1 pulls together, in one location, the literature that is available on living snow fences. The available literature on LSF includes scholarly articles, books, fact sheets and pamphlets from state departments of forestry and departments of transportation, and general websites with information on the topic. The living snow fence topic includes such subjects as living snow fences, windbreaks, plant characteristics, design and effectiveness of LSF and windbreaks, and principles of snow movement. Searching for literature on LSF was accomplished by searching the available databases in the Syracuse University and SUNY-ESF libraries system. Databases searched included Agricola, BioOne, CSA Illumina, IngentaConnect, ProQuest Research Library, ScienceDirect, Scopus, SpringerLink, Web of Science, and WorldCat. Google and Google Scholar

were also used to find literature on living snow fences, and often results from those searches linked to articles found in the aforementioned databases. The following search terms were used in all searches (and combinations of these terms were also used using Boolean logic and truncation where appropriate): living snow fence, living snow fence*, living snowfence*, snowfence*, windbreak*, living snow fence plant characteristics, windbreak plant characteristics, living snow fence plants, blowing snow, snow movement, and snow control. Once a relevant article or resource was located, an abstract was found and the citation for the article and abstract was added to the list of resources. If there was no abstract to be found on the web for an article, a brief summary of the article or web page was written highlighting its relevance to the living snow fence topic. Articles and information previously found about LSF were also added to the literature review, and abstracts were searched for and added as well. When abstracts were not available, a summary was created as mentioned before. Because of the relatively large number of items found in these searches, the literature is grouped by categories.

The categories are as follows:

- Blowing and Drifting Snow
- Controlling Snow
- Cost/Benefits/Effects
- Ecological and Agricultural Aspects
- Living Snow Fences
 - Design
 - Installation and maintenance
 - Plants
- Programs
- Research

Blowing and Drifting Snow

The literature in this category discusses different aspects of blowing and drifting snow. Blowing snow creates drifts that form in particular patterns and understanding this process helps in designing a living snow fence for specific sites. These articles articulate how snow is blown and forms drifts and how LSF or other barriers aid in preventing snow from piling up on major roadways.

Alhajraf, S. (2004). Computational fluid dynamic modeling of drifting particles at porous fences. *Environmental Modelling and Software*, 19, 163-170. Retrieved from ScienceDirect. Elsevier Syracuse University, Syracuse, NY. 13 May 2009 <http://www.sciencedirect.com/>

Abstract: This paper introduces a computational fluid dynamic (CFD) model for two and three-dimensional simulation of wind blown particles such as sand, soil or snow. The model is based on the homogenous two-phase flow theory, where the flow field is predicted by solving Navier–Stokes equations for transient, incompressible viscous flow. The particle volume fraction is predicted by solving the transport convection/diffusion equation. Particles transported by suspension and by saltation modes are modeled separately and added to the transport equation as extra source terms. A new solid interface boundary is introduced to the flow computational domain as particles

accumulate to form deposition regions. The model treats control volumes fully blocked by particles as solid surfaces whenever the deposition conditions are satisfied. The transport equations are discretized in Eulerian reference frame using finite volume method. The model is used to simulate the flow field around fences for two applications, snow drift at single row fence and sand drift at double row fence. In both cases, the model shows good agreement with observations and a realistic behavior of the snow and sand particles that deposited at porous fences as compared with both field and wind tunnel measurements.

George, E.J., D. Broberg, and E.L. Worthington. (1963). Influence of various types of field windbreaks on reducing wind velocities and depositing snow. *Journal of Forestry* 61, 345-349. Retrieved from IngentaConnect. 13 May 2009 <http://pi2.ingenta.com/>

Abstract: Comparisons were made of wind velocities and snowdrift patterns on the windward and leeward sides of windbreaks and slat barriers of varying numbers of rows, designs, and densities. Density was determined by placing a dotted grid over a picture enlargement and then computing the space occupied. Windbreaks and barriers which were permeable in the lower half of the structure caused snowdrifts to form over a wider area than the less permeable ones. Such permeable structures also reduced most erosive wind velocities to a nonerosive rate. Between a series of windbreaks spaced 400 feet apart wind velocities and snowdrift deposits indicated the series had no cumulative effect on wind reduction. Proper tillage practices must still be used in conjunction with windbreaks or other structures to control wind erosion of fields.

Sato, Toshimi, et. al. (2002). New method for evaluation of blowing snow measures through cold wind tunnel experiment and CCD image analysis. *Proceedings of the XIth International Winter Road Congress*. Highway Research Board.

Abstract: This paper describes a new method by which the effect of poor visibility improvement of the blowing snow measures can be quantitatively evaluated through the analysis of CCD image of blowing snow occurring in a cold wind tunnel device. The new method enables the selection of the most effective measure dependent on the in-situ conditions before site installation.

Schmidt, R.A. (1982). Properties of blowing snow. *Reviews of Geophysics and Space Physics* 20(1), 39-44. Retrieved from Scopus. Elsevier. Syracuse University, Syracuse, NY. 13 May 2009 <http://www.scopus.com/>

Abstract: The size and shape of windblown snow particles determine not only the mass transported by turbulent fluxes but also the rate of phase change from ice to water vapor that occurs in this multiphase flow. These properties and particle densities dictate particle fall velocity and therefore the vertical distribution of mass and surface area, which strongly influence the gradients and fluxes of sensible heat and water vapor within the transport layer.

Shulski, M. and M. Seeley. (2003). Climatological characterization of snowfall and snow drift in Minnesota (for the design of living snow fences). *Analysis of Snow Climatology*. Minnesota Department of Transportation. 1 Oct. 2003. Retrieved from http://climate.umn.edu/snow_fence/intro.html

Summary: This article addresses the problem in the Upper Midwest of blowing and drifting snow on roads and highways and a solution to that problem. The solution involves building LSF along roadways, and this article discusses the reasons why the Minnesota Department of Transportation is planting LSF to control drifting snow. The article also discusses the importance of understanding certain climatological factors that need to be investigated to effectively design living snow fences.

Tabler, R.D. (1975, Jul.). Estimating the transport and evaporation of blowing snow.

Proceedings of the Great Plains Agriculture Council Publication 73, Snow Management on the Great Plains Symposium, 85-104. Retrieved from CSA Illumina. Proquest. 13 May 2009 <http://mdl.csa.com/>

Abstract: Complexity of the physical processes does not permit the transport and evaporation of wind-blown snow to be estimated from a purely theoretical analysis. This paper describes a simplified conceptual model based on the maximum distance that a particle can travel before complete evaporation, and derived from consideration of the consequences of a non-uniform particle size distribution. Model predictions agree well with snow accumulations measured at numerous sites in southeast Wyoming over several years. Results indicate a significant portion of the winter's precipitation is lost to in-transit evaporation on sites where snowfall is relocated by wind. An example is given of how this model can be used to assess effects of land management practices on the transport and evaporation of blowing snow.

Tabler, R.D. (1980). Geometry and density of drifts formed by snow fences. *Journal of Glaciology* 26(94), 405-419. Retrieved from Scopus. Elsevier. Syracuse University, Syracuse, NY. 13 May 2009 <http://www.scopus.com/>

Abstract: Presents results from studies of snow-drifts formed by vertical-slat 'Canadian' and horizontal-slat 'Wyoming' snow fences having 50% porosity and heights H from 0.8 to 3.8m, on nearly level terrain. Polynomial regression equations are fitted to drift profiles for both fence types.

Takeuchi, M. (1980). Vertical profile and horizontal increase of drift-snow transport. *Journal of Glaciology* 26(94), 481-492. Retrieved from Scopus. Elsevier. Syracuse University, Syracuse, NY. 13 May 2009 <http://www.scopus.com/>

Abstract: The horizontal distribution of drift flux was measured with snow traps along a transect parallel with the wind, beginning at an up-wind boundary that served as the starting point of drifting snow. Results indicate that drift-snow transport cannot be defined uniquely unless the drifting snow attains equilibrium (i.e. the snow profile is saturated).

Controlling Snow

Articles in this section are relevant to how snow can best be controlled. Most methods of controlling snow that are discussed are by the use of a living snow fence or windbreak. Examples of snow fences that are effective in controlling snow buildup on roadways are given.

Bilbro, J.D. and D.W. Fryrear. (1988). Annual herbaceous windbarriers for protecting crops and soils and managing snowfall. *Agriculture, Ecosystems and Environment*, 22-23, 149-161. Retrieved from Science Direct. Syracuse University, Syracuse, NY. 13 May 2009 <http://www.sciencedirect.com/>

Abstract: Annual herbaceous windbarriers can have certain advantages over perennial woody shelterbelts in that they are easier, faster and cheaper to establish, and may allow more flexibility in the farming operation. Their primary function is to reduce windspeed, which in turn generally improves growing conditions for the adjacent plants by improving temperature and moisture conditions. Annual windbarriers can be effective in increasing crop yields, controlling wind erosion, preventing sandblast damage to crop plants and trapping snow where it will be of maximum benefit in increasing soil water. Barrier porosity should be 65–75% for snow management and 40–50% for all other applications. Plants used should be as resistant to lodging as possible. Barriers should be comprised of two or more rows of plants, oriented perpendicular to the erosive or snow-laden winds (or in a serpentine manner if there is no predominant wind direction), spaced properly and established early enough to give the necessary protection to the adjacent area.

Blackburn, R.R., D.E. Amsler, and K.M. Bauer. (2003, 13-17 July). Guidelines for snow and ice control materials and methods. Presentation. 10th AASHTO/TRB Maintenance Management Conference. Duluth, MN: Midwest Research Institute.

Summary: This print-out of a presentation gives guidelines for snow and ice control on highways based on a study of tactics used to control snow and ice. There is information on what kinds of tactics to use for certain amounts and kinds of snow and ice, such as using chemicals. This presentation does not have any information on snow fences; however, the information provided would be useful for determining the value of snow fences, whether living or not, as an effective tactic in controlling snow and ice on highways.

Managing drifting snow. (2001, Sep.-Nov.). *Technology News*. 11 May 2009 Retrieved from http://www.ctre.iastate.edu/pubs/Tech_News/2001/sepoct/managesnowdrift.pdf

Summary: This newsletter discusses how to manage drifting snow by various methods, including living snow fences.

Minsk, L.D. (1998). *Snow and ice control manual for transportation facilities*. New York: McGraw-Hill, 15 May 2009 Retrieved from <http://ntlsearch.bts.gov/tris/record/tris/00784107.html>

Abstract: Though there has been a low level of research into improved techniques and equipment for snow and ice control since the end of World War II in the United States, and to a greater extent in Europe and Scandinavia, it wasn't until the last decade of the twentieth century was well advanced that a concerted effort to address this deficiency was initiated. Annual costs of snow and ice removal and control have been climbing for many years and now total well over \$2 billion in the United States. With costs becoming an increasing burden, government agencies both large and small have realized that the lagging technology must be improved to cope with the

increasing demands for more efficient operations. Research has now resulted in better designs of equipment for the removal task. New technologies have introduced new practices which are now reducing the deleterious environmental consequences of the massive amounts of chemicals once used for deicing. The technology of snow and ice control is not static. Therefore the emphasis of this book is on the fundamentals of snow and ice control, that is, the available technology and the scientific underpinnings of that technology, rather than a cookbook account of what actions to take or what procedures to follow. In our view, this will better prepare those most intimately involved with the critical task of ensuring the best performance of our transportation systems under adverse winter conditions. The goal is to provide the reader with a firm foundation that will enable him or her to assess the value of current and proposed equipment and techniques.

Peterson, T.C. and R.A. Schmidt. (1984). Outdoor scale modeling of shrub barriers in drifting snow. *Agricultural and Forest Meteorology* 31, 167-181. Retrieved from ScienceDirect. Elsevier. Syracuse University, Syracuse, NY. 13 May 200 <http://www.sciencedirect.com/>

Abstract: Model shrub barriers one-twentieth the average height of corresponding mature plants were exposed to snow drifting on a frozen lake, to test the effects of barrier porosity and row spacing on snow accumulation. Single rows with porosities of 8, 15, and 23% produced drifts with average cross-sectional areas of $9H^2$, where H is model height. The area of the average deposition downwind of a 36% porosity model was $12H^2$. Total deposition behind two model shrub rows spaced 8, 10 and 14H apart, perpendicular to the wind, was greatest for the largest spacing. At this spacing, the minimum snow depth between rows was 0.5H. The experiments demonstrate the importance of maintaining porous barriers. Gaps, simulating shrub mortality, greatly reduced snow storage, especially during high winds. Results from this investigation indicate that a porous shrub in rows spaced at least 14 times the average barrier height, would provide good snow distribution for forage production between rows.

Tabler, R.D. (2006). Three-dimensional roughness elements for snow retention. Final Report FHWA-Wy 06/04F. Niwot, Colorado: Tabler and Associates. 15 May 2009 Retrieved from <http://ntlsearch.bts.gov/tris/record/tris/01042044.html>

Abstract: The objective of this study was to develop a practical and economical method of retaining snow along roadsides in order to reduce icing caused by blowing snow. Although multiple rows of conventional 4-ft snow fence could serve this purpose, it was hypothesized that a three-dimensional array of elements might be more effective and aesthetic, and might prove to be more economical. An idea leading to the research reported here was for tetrapodal elements constructed from 2" x 4" lumber, and this was later expanded to include the development and testing of tubular, wire frame-supported plastic netting. The study consisted of developing, testing, and comparing these alternative roughness elements. Conclusions from this study are as follows: The 3-ft-tall tetrapod developed in this study is an efficient design that minimizes costs for materials and labor. Tetrapods are the most costly element to fabricate and install and the physical structure of tetrapods presents a potential collision hazard to errant vehicles. Tank baffles are effective in collecting snow, but their cost is approximately twice that of tetrapods. Snow snakes are significantly less costly than tetrapod arrays, and their cost per unit volume of snow storage is comparable to that of conventional snow fence of equal height installed on wood or steel posts. The primary advantages

of snow snakes over conventional snow fences are their unobtrusive appearance, and the fact that they present no hazard to errant vehicles. They also promote the reestablishment of vegetation by increasing soil moisture, providing shade, and by providing protection from wind and grazing animals. Snow snake drifts in medians would also help to restrain vehicles that would otherwise cross over into oncoming traffic.

Cost/Benefits/Effects

The literature contained in this section includes papers on the costs, benefits and effects of living snow fences. LSF can be costly and take a while to become effective, but they have many benefits such as being more aesthetically pleasing compared to structural fences and they add to the natural landscape. Also, how the living snow fence is designed will produce certain effects. Some of these papers discuss what happens to the snow when blocked by a snow fence and how this benefits roadways and crops.

Benefit/cost ratio economic analysis. (2004). ADOT Traffic Engineering Policies, Guidelines, and Procedures.

Summary: This document is a part of the larger Arizona DOT Traffic Engineering Policies, Guidelines, and Procedures document which serves “as a guide for department personnel and consultants for traffic studies, operation, and design.” The economic analysis provides some information on how snow fences have aided in reducing the rate of accidents due to snowy pavement.

Bird, P.R. (1998). Tree windbreaks and shelter benefits to pasture in temperate grazing systems. *Agroforestry Systems*, 41(1), 35-54. Retrieved from SpringerLink. 13 May 2009
<http://www.springerlink.com/>

Abstract: The effects of windbreaks on pastures are reviewed, with an emphasis on temperate grazing systems. Mechanisms of plant response to shelter are dealt with in brief. Few papers on measured responses of pasture species to shelter were located in a search of the global literature for the period 1972–97. Except in cold climates, where the benefits of snow-trapping on water availability can be demonstrated, there were few reports of increased production of pasture in response to shelter. A significant result was obtained in a summer rainfall environment in Australia, where a 43% increase in wool production was obtained over three years in small plots sheltered with iron sheeting on the fences. The gain was attributed to increased pasture growth. In New Zealand, one study over three years with a narrow, permeable shelterbelt in a windy, dry summer environment showed a 60% increase in pasture growth in the sheltered zone. However, another study on a high rainfall site with a dense, wide shelterbelt found no substantial shelter effect on pasture. In dry, hot and windy climates there appears to be scope for protecting spray-irrigated pasture with windbreaks. The feasibility of evaluating shelter effects on pastures or crops from old windbreaks is questioned. Variability of soil over the site cannot be satisfactorily accounted for and there are problems in defining the true ‘unsheltered’ yield. Shelter effects on pastures could best be determined by comparing production in small completely sheltered plots and open plots. Effects in and near the competitive zone should be measured for living windbreaks. Modelling could then be used to evaluate windbreak systems. We are not yet in

a position to provide unequivocal advice to farmers on windbreak outcomes for particular purposes or regions.

Brandle, J. and L. Hodges. (n.d.). Field windbreaks. Extension Publication EC1778. Lincoln, NE: University of Nebraska. 13 May 2009 Retrieved from <http://www.ianrpubs.unl.edu/epublic/pages/index.jsp>

Summary: This brochure explains how field windbreaks can increase crop yields while at the same time reducing inputs and improving environmental quality and production efficiency.

Brandle, J.R. and S. Finch. (n.d.). How windbreaks work. Extension Publication EC1763. Lincoln, NE: University of Nebraska. 13 May 2009 Retrieved from <http://www.ianrpubs.unl.edu/epublic/pages/index.jsp>

Summary: In this brochure, learn how windbreak structure -- height, density, number of rows, species composition, length, orientation and continuity -- determines how effective the windbreak will be in reducing wind speed and altering microclimate.

Daigneault, W. and Betters D. R. (2000). A comparison of the economic efficiency of living and artificial snowfence designs for road protection. *Western Journal of Applied Forestry* 15(2), 70-74. Retrieved from Agricola. IngentaConnect. Syracuse University, Syracuse, NY. 11 May 2009 <http://www.ingentaconnect.com/>

Abstract: Both artificial and living snowfences are used to protect roads from blowing and drifting snow. This article evaluates and compares the economic performance of three snowfence designs-- the Wyoming and double-row slatted artificial snowfences and a three-row living snowfence. The economic analysis evaluates the snowfences by applying four economic performance indicators: total net benefits, present net value, benefit/cost ratio, and annual breakeven benefits. The study uses snow removal savings and accident reduction benefit information from a case study in the state of Wyoming. The case study results show all the designs are economically efficient when used for road protection. However, the living snowfence outperformed the other designs in three of the four economic performance indicator categories. The largest proportion of total costs of the Wyoming and living snowfence are establishment costs whereas the bulk of total cost of the double-row slatted snowfence is for maintenance. The economic performance of all the snowfences is most sensitive to changes in their useful or effective lives. The procedures and general conclusions of the study can be applied to similar cases elsewhere.

Heisler, G.M. and D.R. Dewalle. (1988). Effects of windbreak structure on wind flow. *Agriculture, Ecosystems and Environment* 22(23), 41-69. Retrieved from Scopus. Elsevier. Syracuse University, Syracuse, NY. 13 May 2009 <http://www.scopus.com/>

Abstract: Functional effects of windbreaks are directly related to the effects of windbreaks on air flow. Additionally, the indirect effects of windbreaks on air temperature and humidity are interrelated with the effects of air movement. The horizontal extent of windbreak effects upwind and downwind is usually assumed to be proportional to windbreak height, h. Measureable

reductions in windspeed have been recorded as far as 50 h to the lee of windbreaks, and rarely, even farther. Reductions of 20% or more may extend to about 25 h from the windbreak. For windbreaks that are long relative to their windbreak height, the most important structural feature is porosity. Maximum wind reductions are closely related to porosity, with low porosity producing high maximum reductions. Barriers with very low porosity create more turbulence downwind than medium-dense barriers. The higher turbulence may result in recovery of mean horizontal windspeeds to upwind speeds closer to low-porosity barriers, thus resulting in a shorter protected distance. However, the reduction in protected distance with very dense windbreaks compared to medium dense windbreaks is much less than much of the older literature suggests. Turbulence in the approach flow reduces windbreak effectiveness, particularly at far downwind positions. The turbulence may be caused by thermal instability, a rough ground surface, or other upwind barriers to flow. Differences in approach-flow turbulence, differences in height of measurement relative to windbreak height and differences in vertical porosity gradients are responsible for much of the scatter in experimental data. There is a triangular 'quiet' zone below a line beginning near the top of windbreaks and extending to near ground level at a distance of about 8 h to the leeward. In this zone, the turbulent velocity fluctuations are reduced below values in the approach flow. Above and downwind of the quiet zone is a 'wake' zone with turbulent fluctuations greater than those in approach flow. The magnitude of turbulent velocity fluctuations in the lee of windbreaks is inversely proportional to porosity. However, there is a larger difference in turbulence generated between solid barriers and slightly porous barriers than between slightly porous and very porous barriers. Windbreaks generally reduce turbulent eddy length, thus increasing the peak frequency of turbulent velocity fluctuations, regardless of their structure. Peak frequency of velocity fluctuations close to windbreaks tends to increase with porosity.

Josiah, S.J., S. Prestin, and D. Gullickson. (n.d.). The value of managed snow: benefit/cost analyses of LSF in Minnesota. Journal Series No. 13256, Agricultural Research Division, University of Nebraska.

Abstract: This paper examines the benefits and costs of LSF in the Upper Midwestern United States. While LSF are often promoted as an effective and well- tested means to control blowing and drifting snow along public highways, their economic performance has not been adequately documented. A recent living snow fence establishment program in Minnesota (upper Midwestern United States) provided an opportunity to determine economic impacts. Project participants provided site and living snow fence project descriptions, road usage statistics, and establishment and maintenance costs for the areas to be protected. Using these data, quantities (in tons) of snow expected to be trapped by living snowfences before it reached roadways were calculated, and estimates for subsequent savings for snow removal determined. The United States Federal Emergency Management Agency (FEMA) Riverine Limited Data Benefit-Cost Module for Hazard Mitigation Projects was then used to develop benefit-cost information for each proposed project. Benefit:Cost (B:C) ratios for a sample of 44 sites averaged 29:1 on private lands, and 83:1 on public lands. These conservative analyses included only snow removal costs for an average winter snowfall accumulation season (32" or 0.81m), and used US\$1/ton for snow removal costs (severe storms can cost from US\$3-US\$5/ton for snow removal). B:C ratios would likely increase if environmental benefits, or other benefits gained from avoiding road closures were included, such

as reduced loss of commerce, and enhanced public safety, or if the snowfences generated income through the production of commercially valuable products.

Kelson, A.R., R.J. Lillieholm, and M.R. Kuhns. (1999). Economics of LSF in the intermountain west. *Western Journal of Applied Forestry* 14(3), 132-136. Retrieved from IngentaConnect. 13 May 2009 <http://www.ingentaconnect.com/>

Abstract: Past research has found that LSF are the most cost-effective option for controlling blowing snow along transportation corridors. Despite this, LSF are an underutilized forestry practice throughout much of the Intermountain West, even though these fences can be successfully maintained in the region's harsh climate. Decision-makers may be encouraged to establish more LSF in the region when economic efficiency gains can be demonstrated. Efficiency gains from living snow fences, evaluated using the annualized cost approach, demonstrate that the benefits to society outweigh the costs. An example is presented using an average-sized, 1,040-ft-long, 3 row snow fence, and a discount rate of 8%. To offset snow fence costs over a 50 yr expected life, the fence need only reduce traffic accidents by as little as one every 23 yr, or reduce snow plowing by about 6 hr/yr. Other likely but less quantifiable benefits make the benefits of LSF even more economical to society. Private expenditures may need to be subsidized if these social benefits are to be provided at optimal levels, however

Living snow fence reduces costs, maintenance. (2002, Apr.-Jun.). *Technology Exchange Newsletter*. 16 Oct. 2003 Retrieved from <http://www.mnltap.umn.edu/Publications/Exchange/2002-2/SnowFence.html>

Summary: This article discusses briefly the benefits and basics of design of living snow fences. It also describes the program developed in Minnesota to plant living snow fences, and the progress of the program at the time of publication (2002).

Snow control structures. (1997, Feb.). *Road Talk* 4.

Summary: This short article describes the trade-offs of building snow fences as opposed to simply using existing corn fields as a means of controlling accumulating snow. A permanent snow fence is the most cost effective in the long term scheme and the use of cornstalk is only cost effective for the short term.

Spielman, J. and J.A. Dickerson. (n.d.). Why plant windbreaks? Selling windbreaks in the Northeast states.

Summary: This article discusses the uses and benefits of windbreaks in the Northeast in an effort to persuade the public to plant them. Some of the reasons discussed are energy conservation, livestock and wildlife comfort, crop protection, and control of soil erosion.

Tabler, R.D. (2003). Controlling blowing and drifting snow with snow fences and road design. Final Report. Niwot, CO: Tabler and Associates.

Summary: This article discusses the benefits of snow fences along roadways, including reduction in snow and ice removal costs, vehicle crashes, road closures, and pavement maintenance costs. Snow fences greatly reduce drifting snow which leads to poor visibility and slush and ice build-up. The results of a study on the installation of snow fences along I-80 in Wyoming are reported. This snow fences installed in Wyoming have been very successful in exhibiting all the benefits listed, especially in reducing the cost of snow removal by equipment.

USDA Natural Resources Conservation Service. (2006, Nov.). Conservation Practices that Save: Windbreaks/Shelterbelts. Save Energy Save Money. 18 May 2009 Retrieved from <http://www.mainerural.org/energy/fieldguide/windbreaks.pdf>

Summary: This article describes how windbreaks, shelterbelts and LSF have helped reduce energy usage in residential areas, as well as in snow removal efforts.

Ecological and Agricultural Aspects

These articles discuss how LSF affect the ecology of the site and the importance of LSF to agriculture. Many of these papers discuss how windbreaks are beneficial to farms and other agricultural systems. The importance of agroforestry is also discussed and how LSF are a part of agroforestry and can be used to improve the local environment. LSF also aid in conservation efforts of wildlife and to help decrease soil erosion.

Brandle, J.R., L. Hodges, and X.H. Zhou. (2004). Windbreaks in North American agricultural systems. *Agroforestry Systems* 61(2), 65-78. Retrieved from Web of Science. ISI Web of Knowledge. Syracuse University, Syracuse, NY. 11 May 2009. <http://apps.isiknowledge.com/>

Abstract: Windbreaks are a major component of successful agricultural systems throughout the world. The focus of this chapter is on temperate-zone, commercial, agricultural systems in North America, where windbreaks contribute to both producer profitability and environmental quality by increasing crop production while simultaneously reducing the level of off-farm inputs. They help control erosion and blowing snow, improve animal health and survival under winter conditions, reduce energy consumption of the farmstead unit, and enhance habitat diversity, providing refuges for predatory birds and insects. On a larger landscape scale windbreaks provide habitat for various types of wildlife and have the potential to contribute significant benefits to the carbon balance equation, easing the economic burdens associated with climate change. For a windbreak to function properly, it must be designed with the needs of the landowner in mind. The ability of a windbreak to meet a specific need is determined by its structure: both external structure, width, height, shape, and orientation as well as the internal structure; the amount and arrangement of the branches, leaves, and stems of the trees or shrubs in the windbreak. In response to windbreak structure, wind flow in the vicinity of a windbreak is altered and the microclimate in sheltered areas is changed; temperatures tend to be slightly higher and evaporation is reduced. These types of changes in microclimate can be utilized to enhance agricultural sustainability and profitability. While specific mechanisms of the shelter response remain unclear and are topics for further research, the two biggest challenges we face are: developing a better understanding of why producers are reluctant to adopt windbreak technology and defining the role of woody plants in the agricultural landscape.

Clark, W.R. and K.F. Reeder. (2007). Agricultural buffers and wildlife conservation: a summary about linear practices. Fish and Wildlife Response to Farm Bill Conservation Practices. Ed. J.B. Haufler. The Wildlife Society, Technical Review 07-1, 45-55. 18 May 2009 Retrieved from http://www.fsa.usda.gov/Internet/FSA_File/chap_3.pdf

Abstract: Conservation practices such as filter strips, grassed waterways, buffers, contour strips, riparian buffers, windbreaks and shelterbelts are eligible under a variety of USDA programs. Most were originally designed to provide benefits regarding reduced soil erosion and improved water quality. Most often grasses, or mixtures of grasses and forbs, are used in these practices, although establishment of trees and shrubs is encouraged in some practices. The small area and high edge-area ratios limit the usefulness of these practices for wildlife. Scientific evidence suggests that enrolling land in linear practices has accumulated in recent years, although most studies still focus heavily on benefits to birds and do not address the larger questions of the animal communities. With careful planning and management, applying linear practices widely within an agricultural landscape could be expected to have positive wildlife benefits compared with continued intensive row cropping.

Ganguli, A., et. al. (2008, Dec.). When are native species inappropriate for conservation plantings? *Rangelands*, 27-32. Retrieved from BioOne. Syracuse University, Syracuse, NY. 12 May 2009 <http://www.bioone.org/>

Summary: This article is about whether native or nonindigenous tree species should be used in conservation plantings. The article briefly describes how certain species have been planted for soil stabilization and for living snow fences. It also contains a chart outlining the distribution and purpose (including windbreaks and living snow fences) for planting eastern red cedar seedlings in several states.

Johnson, R.J., M.M. Beck, and J.R. Brandle. (n.d.). Windbreaks and wildlife. Extension Publication EC1771. Lincoln, NE: University of Nebraska. 13 May 2009 Retrieved from <http://www.ianrpubs.unl.edu/epublic/pages/index.jsp>

Summary: This brochure provides an overview of how windbreaks can benefit wildlife and what trees, shrubs and planting designs to consider for various wildlife habitats.

Josiah, S.J. and J. Kemperman. (1998, Nov.). Emerging agroforestry opportunities in the upper Midwest. *Journal of Forestry*. 4-9. Retrieved from Web of Science. ISI Web of Knowledge. Syracuse University, Syracuse, NY. 12 May 2009. <http://apps.isiknowledge.com/>

Abstract: Agroforestry, the integration of trees and shrubs into agricultural systems, is thriving in the upper Midwest because of changing farm economics, new plant materials, useful research results, and growing markets for specialty forest products. Shelterbelts, riparian zones, living snow fences, and short-rotation plantations all create opportunities for environmentally friendly profit. Agroforestry's transdisciplinary nature requires partnerships, however, and although more

landowners are practicing agroforestry, today's scattered installations need to be integrated into a systems approach if agricultural landscape management is to improve.

Long-term snow-fence experiments to examine effects of altered climate in arctic and alpine tundra. (1997). Tundra Ecosystem Analysis and Mapping Laboratory. 15 Feb. 2001. Retrieved from <http://culter.colorado.edu:1030/Niwot/Snowfence/intro.html>

Summary (from introduction): The response of ecosystems to altered winter precipitation patterns as predicted by current global change estimates is unclear (Walker et al., 1993). An experiment in the Colorado alpine and Alaskan Arctic is examining the short- and long-term effects of altered climate regimes on tundra vegetation (Walker et al., 1994). Large snow fences and small portable greenhouses are being used to examine the effects of altered snow regimes and air temperatures (Welker et al., 1997 submitted). Tundra vegetation communities do not equilibrate quickly because changes to the belowground resources and the substrate require long periods to adjust and a series of transient plant communities unlike existing ones may occur. For this reason, we have designed an experiment with the intent of observing ecosystem change over a much longer time period than the standard 3-5 year ecology experiment (Walker et al., 1994). The following web pages describe the experimental design and the short-term changes to the physical and biological components of the system. The experiment is part of the NSF-sponsored Long-Term Ecological Research (LTER) project on Niwot Ridge, CO (NWT LTER), and the International Tundra Experiment (ITEX) (Molau and Molgaard, 1996) at Toolik Lake, AK.

Quam, V.C., et. al. (n.d.). Windbreaks in sustainable agricultural systems. Extension Publication EC1772. Lincoln, NE: University of Nebraska. 13 May 2009 Retrieved from <http://www.ianrpubs.unl.edu/epublic/pages/index.jsp>

Summary: Information on integrating windbreaks and agroforestry practices into sustainable agricultural systems to enhance the local environment and add profitability.

Sampson, N. (1992). Forestry opportunities in the United States to mitigate the effects of global warming. *Water, Air and Soil Pollution* 64, 157-180. Retrieved from SpringerLink. 12 May 2009 <http://www.springerlink.com/>

Abstract: There are a variety of opportunities in the United States to expand the area of trees and forests, and to improve their growth, that could have significant impact upon the annual uptake of atmospheric CO₂. Work coordinated by the American Forestry Association has attempted to quantify those opportunities, and demonstrate what kinds of costs and benefits might result from an attempt to begin implementing them. The first section of the work, reported in this paper, has focused on the opportunities that are seldom thought of as regular forestry- planting trees on marginal crop and pasture lands, increasing windbreaks and shelterbelts, growing trees as a biomass energy source, and improving urban tree canopies and placements as an energy-conserving measure. The benefits from such work include the C sequestered in the biomass and soils involved, as well as the carbon emission reductions achieved through energy conservation. These opportunities could add up to a total C impact per year in the range of 141 to 382×10⁶t-somewhere between 10 and 30% of the current net C emission from fossil fuel in the United States. Additional

work is underway to quantify the opportunities inherent in improving the management of existing forestlands, through more traditional forestry. The results of that work will be available in late 1992.

Schoeneberger, M.M. (1992). Enhancing biodiversity with and within agroforestry plantings. USDA Forest Service – National Agroforestry Center. Lincoln, NE: University of Nebraska. 13 May 2009 Retrieved from <http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1027&context=usdafsfacpub>

Abstract: Agroforestry is the deliberate introduction of multipurpose woody perennials (MWP) into agroecosystems for the purpose of enhancing agricultural productivity, natural resource conservation, and human environments. This introduction promotes biodiversity within the agroecosystem and thus its sustainability. This biodiversity is only a fraction of its potential due to the limited number and arrangement of the MWPs currently used in agroforestry plantings. An expanded effort in nursery and agroforestry research and development along with nursery production of diverse, adapted MWPs will need to be pursued to fully capitalize on agroforestry's economic and ecological benefits. [Also, paper has section on living snow fences.]

Shelterbelts for dugouts. (2003). Indian Head, SK, Canada: AAFC-PFRA Shelterbelt Centre.

Summary (from introduction): Water supply has always been a primary concern of prairie producers. To secure a reliable source of water, many generations of farmers have developed farm dugouts. Trees planted around a dugout increase the quantity of water stored in the dugout and may help to improve water quality. The combination of trees and water greatly enhance an area for wildlife by providing a dependable water source and wildlife habitat. This brochure gives reasons for why a shelterbelt around a dugout is beneficial and instructions in the design and planting of such a shelterbelt.

Sykes, K.J. and M. Majeski. (n.d.). Agroforestry – What is it? Can you benefit from it? Forest Management Update 20, 35-41. 12 May 2009 Retrieved from <http://www.na.fs.fed.us/pubs/fmu/i20/article5.pdf>

Summary: This article provides a basic history and description of agroforestry. The purpose and benefits of windbreaks is discussed in detail with mention of living snow fences.

Living Snow Fences

This section includes papers on design, installation and maintenance of living snow fences, and plants that can be used in them. This section is split into the sub-categories: design, installation and maintenance and plants. Articles in these sub-categories overlap; articles listed in installation and maintenance will also be relevant to designing living snow fences.

Design

This sub-category includes literature on how to design a living snow fence and the many factors that must be considered in setting up the proper design for a specific site. There are examples of specific LSF and how they were designed.

Brandle, J.R. and H.D. Nickerson. (n.d.). Windbreaks for snow management. Extension Publication EC1770. Lincoln, NE: University of Nebraska. 13 May 2009 Retrieved from <http://www.ianrpubs.unl.edu/epublic/pages/index.jsp>

Summary: This brochure provides guidance for designing a windbreak to manage snow for a particular purpose such as spreading snow across a large area or confining it to a small area to capture moisture and control drift.

Gullickson, D., S.J. Josiah, and P. Flynn. (1999). Catching the snow with living snow fences. St. Paul, MN: University of Minnesota.

Summary (from inside cover): While the need for and usefulness of LSF is becoming increasingly well accepted, until now there has been no one comprehensive source of information to help those interested in properly designing, locating, and establishing living snow fences. This guide is designed to meet these needs. Proper location and design is particularly important to living snow fences, because improperly placed or designed plantings can exacerbate problems they were intended to solve. No abstract was available online; a request to Interlibrary Loan was made.

Josiah, S. and Mike Majeski. (2002). Living snow fences. CINRAM, University of Minnesota. Retrieved from <http://www.extension.umn.edu/distribution/naturalresources/DD7277.html>

Summary: This article is about designing a living snow fence and a program to build fences. It also contains information about effective barrier height, density, length, setback distance and plant species to be used.

Kenney, W.A. (1992). The role of Salicaceae species in windbreaks. *Forestry Chronicle* 68(2), 209-213. Retrieved from Web of Science. ISI Web of Knowledge. Syracuse University, Syracuse, NY. 12 May 2009. <http://apps.isiknowledge.com/>

Abstract: Windbreaks and shelterbelts have long been known to provide valuable amelioration of the environment to reduce wind erosion; improve crop yields; reduce heating costs in buildings; protect livestock; control snow drifting; provide wildlife habitat; improve the aesthetics of rural landscapes; etc. The efficiency of a windbreak will be affected by many of its design parameters such as length, height, width, orientation and porosity. Different wind-control objectives will require different designs, particularly with respect to porosity. The specific implications for the use of poplars and willows in windbreaks are discussed in terms of these objectives and design characteristics.

LandOwner Resource Centre and University of Toronto's Faculty of Forestry. (1995). Designing and caring for windbreaks. Extension Notes. 18 May 2009 Retrieved from http://www.lronline.com/Extension_Notes_English/pdf/wndbrk.pdf

Summary: The Designing and Caring for Windbreaks fact sheet produced by the LandOwner Resource Centre and the University of Toronto's Faculty of Forestry gives information on the

design of windbreaks and their uses. It contains a table of windbreak plant species and their respective densities. It also has a table that outlines how suitable each plant species is to specific Ontario soil types.

Martinelli, M. (1973). Snow fences for influencing snow accumulation. Rocky Mountain Forest and Range Experimental Station, Fort Collins, CO. Retrieved from CSA Illumina. ProQuest. 13 May 2009 <http://mdl.csa.com/>

Abstract: The efficiency of snow fences depends on height, density and length of fence, bottom gap, length and maximum depth of lee drift, cumulative effect of a set of tandem fences, tilting of fence, terrain effects, and contributing distance. The snow fence project on Mount Bethel in central Colorado is a practical example of how some of the above items were used to design and lay out snow fences intended to reduce the amount of wind-blown deposited in the starting zone of an avalanche that crosses an interstate highway.

National Cooperative Highway Research Program Project. (2009). Designing for environmental stewardship in construction and maintenance. Environmental Stewardship Practices, Procedures, and Policies for Highway Construction and Maintenance. 25-25 (4). 12 May 2009 Retrieved from http://environment.transportation.org/environmental_issues/construct_maint_prac/compendium/manual/3_10.aspx

Summary: Section 2 of Section 10 in chapter 3 of this compendium discusses how to design snow fences. LSF are discussed at length with guidelines on how to design a living snow fence and how to select tree and shrub species to plant; however, no specific species are named.

Planning farm shelterbelts. (2003, Feb.). Indian Head, SK, Canada: Agriculture and Agri-Food Canada-PFRA Shelterbelt Centre.

Because this document includes design and maintenance information, it is listed in both sections of this paper.

Summary (from introduction): Properly planned shelterbelts provide many benefits to farm families. They reduce wind, control blowing snow, protect livestock, buildings and gardens, and trap snow for dugouts. Shelterbelts also provide habitat for wildlife, decrease energy consumption and beautify the farmyard. This brochure outlines how to plan and design a shelterbelt for a farm. It also lists suggested plant species to plant and how to space them when planting.

Quam, V., et. al. (n.d.). Windbreaks for livestock operations. Extension Publication EC1766. Lincoln, NE: University of Nebraska 13 May 2009 Retrieved from <http://www.ianrpubs.unl.edu/epublic/pages/index.jsp>

Summary: This publication discusses how to plan and plant a windbreak that protects livestock in all seasons and provides long-term economic benefits to the landowner.

Scholten, H. (1981). Effect of field windbreak design on snow distribution patterns in Minnesota.

Agricultural Experiment Station, University of Minnesota Technical Bulletin 329. Retrieved from WorldCat. 12 May 2009 <http://www.worldcat.org/oclc/7382012>

No abstract or full text available online. [requested through ILL] Summary (from introduction): To help farmers design the best possible field windbreak, the author began a study during winter 1961-62, which extended through the January 1975 blizzard, to determine the effect of windbreak density on snow distribution patterns. Snow depth measurements and observations of existing, well-established windbreaks in east central, west central, and northwestern Minnesota were recorded periodically. To understand the results of this study, the reader should first know the important characteristics of the ideal field windbreak species, and how snowdrifts are formed behind field windbreaks.

Characteristics of plants (height growth, branching habits and rooting habits) used in windbreaks are discussed along with different row and tree spacing. Thinning and pruning of trees is also discussed. The tree species used in this study are the Siberian elm, green ash, and red pine, and there is mention of testing other species.

Tabler, R.D. (1984). Snow control with road design and snow fences. Presentation outline. Snow Removal and Ice Control Technical Institute, University of Wisconsin Extension, Madison, WI.

Summary: This document is an outline of a presentation and summarizes the purpose of snow fences and relates them to road design. Snowdrifts can be predicted so that better road planning can take place and snow fences can be built effectively. This presentation explains many mathematical equations that are used to make these snowdrift profile predictions as well as design the appropriate snow fence for a roadway.

Tabler, R. (1991). Snow fence guide. Washington, D.C: Strategic Highway Research Program, Washington, D.C. 14 May 2009 Retrieved from <http://ntlsearch.bts.gov/tris/record/tris/00621080.html>

Abstract: The Strategic Highway Research Program developed this guide on snow fence technology to cover everything maintenance personnel need to know in order to design and locate snow fences. This guide summarizes the results of research by SHRP and others over the last few years. A 21-minute video, 'Effective Snow Fences,' supplements this guide.

Tuskan, G.A. (1986). Wind tunnel simulations of snow load accumulations within six farmstead windbreak designs. *Great Plains Agriculture* 117, 257-258. Retrieved from Agricola. OCLC FirstSearch. Syracuse University, Syracuse, NY. 12 May 2009 <http://newfirstsearch.oclc.org/>

Summary: Experiments on design and configuration of farm windbreaks in North Dakota show that windbreak design does affect snow depth patterns around farm facilities. Three different windbreak designs were tested each with two different plant configurations (six-row mixed species arrangement and a two-row high density arrangement). Two different storm simulations were applied to each windbreak and data was taken (average snow depth, etc.). The two plant

configurations did not appear to differ in the amount of snow displaced, however there were differences in the different designs.

USDA Forest Service, Rocky Mountain Research Station and Natural Resources Conservation Service. (1998). Inside Agroforestry. Lincoln, NE, Winter 1997-1998 Retrieved from <http://www.unl.edu/nac/insideagroforestry/1997winter.pdf>

Summary: This newsletter contains articles about successful LSF and windbreaks. It also includes diagrams of examples of different heights and densities of snow fences which determine how much snow can be stored by such snow fence.

USDA National Agroforestry Center. (2000, Nov. 13). Living snow fences. 11 May 2009 Retrieved from <http://www.unl.edu/nac/aug94/snowfences/snowfence.html>

Summary: This fact sheet of sorts gives general information on living snow fences. It provides a listing of facts and disadvantages to living snow fences. Steps to planning and designing a living snow fence are outlined along with examples of living snow fence in Idaho. There are also recommended plant species for LSF listed.

Wight, B., T.K. Boes, and J.R. Brandle. (n.d.). Windbreaks for rural living. Extension Publication EC1767. Lincoln, NE: University of Nebraska. 13 May 2009 Retrieved from <http://www.ianrpubs.unl.edu/epublic/pages/index.jsp>

Summary: Learn from this brochure how to design a windbreak around a home, ranch, or farmstead to slow the wind, conserve energy, provide snow and dust control and improve working and recreation environments.

Windbreak density: rules of thumb for design. (2007, Sept.). Agroforestry Notes AF Note – 36.

Summary (from introduction): Information on appropriate windbreak density for specific purposes is readily available. For example, living snowfences, crop protection, and snow distribution designs each have different density recommendations. However, information on selecting species and spacing to achieve a specific windbreak density is more difficult to find. Measuring or estimating windbreak density is another problem altogether. This Agroforestry Note provides some basic designs, including example tree species and spacing along with pictures of real windbreaks that represent the three primary ranges of density for which windbreaks are designed.

Installation and Maintenance

This sub-category contains literature on how to plant the living snow fence and then maintain it so that it remains effective. There are many aspects that must be considered and done to keep a living snow fence maintained, such as weed, insect, and disease control. Within many of these papers are suggestions of plants to use.

Barkley, Y.C. (n.d). Living snow fences. University of Idaho Extension Forestry. 15 May 2009. Retrieved from <http://www.cnr.uidaho.edu/extforest/Living%20Snow%20Fences.pdf>

Summary: This brief article describes how trees should be placed in the design of living snow fences, and this information is also included in a table that shows what kind of plants should be planted in single or twin rows in a high to low protection continuum. A second table listed suggested plants for each of the kinds of plants indicated in the first table.

Boehner, P., J.R. Brandle, and S. Finch. (n.d.). Windbreak establishment. Extension Publication EC1764. Lincoln, NE: University of Nebraska. 13 May 2009 Retrieved from <http://www.ianrpubs.unl.edu/epublic/pages/index.jsp>

Summary: This brochure provides information on planning and establishing a windbreak uniquely suited to a particular site, including site preparation, plant material selection, weed control and replanting.

Planning field shelterbelts. (2003, Feb.). Indian Head, SK, Canada: Agriculture and Agri-Food Canada-PFRA Shelterbelt Centre.

Summary (from introduction): Properly planned shelterbelts provide many benefits to farm families. They reduce wind erosion, control blowing snow, protect livestock, trap snow, and increase crop yields. Shelterbelts also provide diversification opportunities, habitat for wildlife, and beautify the farm. This brochure discusses planning, designing, planting, and maintaining a shelterbelt around a farm. It also gives specifics of recommended plant species and row spacing for certain species.

Shaw, D.L. (1988). The design and use of LSF in North America. *Agriculture Ecosystems and Environment* 22(3), 351-362. Retrieved from Web of Science. ISI Web of Knowledge. Syracuse University, Syracuse, NY. 11 May 2009. <http://www.sciencedirect.com/>

Abstract: LSF are rows of trees and shrubs planted to control snow along land transportation routes, and which have the potential to (1) provide snow control, (2) enhance wildlife habitat, (3) provide winter livestock protection, (4) furnish environmental beautification and (5) offer long-term economic benefits. Disadvantages include the difficulty of establishment on some sites, the length of time to reach serviceable height, the high initial cost as compared to some structures, the degree of maintenance during the establishment period and the amount of land required. Primary features of living snow fence location and design include (1) distance from road, (2) length, (3) species, (4) number of rows, (5) spacing and (6) wildlife components. Each of these is discussed at length. Maintenance, which is the effort required to obtain satisfactory survival and growth, can present a number of problems in arid regions with limited precipitation. In such areas, issues which must be dealt with include irrigation, weed control, and protection from grazing livestock, big game animals, rodents, hot, dry winds and grasshopper damage. Solutions to these problems are discussed.

Stange, C. and J.R. Brandle. (n.d.). Windbreak management. Extension Publication EC1768. Lincoln, NE: University of Nebraska. 13 May 2009 Retrieved from <http://www.ianrpubs.unl.edu/epublic/pages/index.jsp>

Summary: This brochure explains how to maintain the health and vigor of a windbreak throughout its life cycle; covers weed control, protection from large animals and rodents, corrective pruning, insect and disease control and property chemical use.

Streed, E. and J. Walton. (2001). Producing marketable products from living snow fences. St. Paul, MN: University of Minnesota. 13 May 2009 Retrieved from <http://www3.extension.umn.edu/distribution/naturalresources/components/DD7646.pdf>

Summary: “In 1999 the Minnesota Interagency Task Force on LSF published a technical guide called *Catching the Snow With Living Snow Fences*. That guide presents the most up-to-date information available anywhere in the country on designing successful LSF (LSFs). This publication is designed to serve as an additional chapter to *Catching the Snow With Living Snow Fences*, as well as a stand-alone publication for those who do not have the technical guide. It is not meant to repeat the topics covered in the technical guide, but rather to add information about producing marketable products in LSFs. The material presented here is the product of research by the Center for Integrated Natural Resources and Agricultural Management (CINRAM) at the University of Minnesota.”

Windbreaks for conservation. (1974). Agriculture Information Bulletin 339, United States Department of Agriculture.

Summary: This booklet from the USDA gives information on the purposes of windbreaks, including living snow fences, and instructions for planning windbreaks for different purposes. Instructions on what kinds of trees to plant, how to prepare the land and plant the trees, and managing the windbreaks are provided. A listing, by regions in the US, of suggested plant species for windbreaks is also provided.

Windbreak/shelterbelt establishment. (2002). Natural Resources Conservation Service, Conservation Practice Standard, U.S. Department of Agriculture. 12 May 2009 Retrieved from <http://efotg.nrcs.usda.gov/references/public/WI/380.pdf>

Summary: This document is a scientific reference from the Natural Resources Conservation Service division of the U.S. Department of Agriculture and provides a listing of purposes of windbreaks/shelterbelts. It gives criteria that must be followed in building windbreaks/shelterbelts in Wisconsin, including: location, designing, managing snow deposition, species arrangement, and other matters. There are also guidelines for plans, specifications, operation and maintenance of windbreaks. Similar documents are available for other states.

Plants

This sub-category consists of papers on specific plants, such as poplar and shrub willow and their usefulness in a living snow fence.

Dickerson, J. (2002). Plant fact sheet: Purpleosier willow. U.S. Department of Agriculture Natural Resources Conservation Service. 13 May 2009 Retrieved from http://plants.nrcs.usda.gov/factsheet/doc/fs_sapu2.doc

Summary: This fact sheet on *Salix purpurea* L. describes how this plant can be used, how to plant it and its usefulness in creating a living snow fence.

Dickman, D.I., et. al. (2001). Poplar culture in North America. NRC Research Press, Ottawa, Ontario, Canada. 12 May 2009 http://books.google.com/books?id=GRtdQYO_ejUC&pg=PP1&dq=Poplar+Culture+in+North+America#PPP1,M1

Summary: This book describes the status and use of poplars in North America. It documents recent scientific and technological advances in studying poplars. The book also summarizes the practical knowledge on growing and using poplars, this includes living snow fences/windbreaks and biomass for energy. The book outlines the silviculture and ecology of poplars as well as characteristics of clones and cultivars used in North America.

Hall, R.L. (2002). Aerodynamic resistance of coppiced poplar. *Agricultural and Forest Meteorology* 3068, 1-20. Retrieved from ScienceDirect. Elsevier. Syracuse University, Syracuse, NY. 13 May 2009 <http://www.sciencedirect.com/>

Abstract: The aerodynamic resistance to the transfer of heat and water vapour, of a canopy of coppiced poplar (*Populus trichocarpa* × *deltoides*) was estimated as the sum of three components; the bulk leaf boundary layer, within-canopy, and roughness-sublayer resistances. These components were calculated from measurements of wind speed and leaf area distribution. Account was taken of enhanced transfer of heat and water vapour over momentum within the roughness sublayer. The resulting estimates of aerodynamic resistance, which are in agreement with values determined more directly from the flux–gradient relationship for sensible heat, are less than for momentum transfer calculated from the classical semi-logarithmic formulae. Consequently, the excess resistance for coppiced poplar at this site was negative.

Trees and shrubs for prairie shelterbelts. (2001, Jan.). Indian Head, SK, Canada: PFRA Shelterbelt Centre.

Summary (from introduction): This booklet summarizes the characteristics and use of trees and shrubs produced by the PFRA Shelterbelt Centre for planting on prairie farms. The information is not presented as a detailed taxonomic description but is designed to provide the user with a means of identifying trees in established belts and in determining desirable species for new plantings.

Programs

The papers in this category include those describing living snow fence programs in different states. Many of these programs were started to alleviate the problems associated with blowing and drifting snow on roadways. These descriptions of programs list plants used, funding for the program, and successes and failures of the programs. Most of the programs are partnerships with the U.S. Department of Agriculture or the states' Department of Transportation.

Claeys, Tom. (2009). North Dakota living snow fence initiative. Report. Bismark, ND: North Dakota Forest Service.

Summary: This paper outlines how North Dakota began a living snow fence program and its progress from 1998 to 2009. The concept behind LSF and their benefits is explained, as well as the goal of the initiative. The report lists general locations of living snow fences, those involved in the task force, grant programs that have aided the initiative, and provides a listing of the things the initiative did right to begin a successful program.

Iowa Department of Transportation. (2002, Jul.). Iowa's cooperative snow fence program. 13 May 2009 Retrieved from <http://ntlsearch.bts.gov/tris/record/tris/00782252.html>

Abstract: While we can't keep it from blowing, there are ways to influence the wind that carries tons of blowing and drifting snow. Periodically, severe winter storms will create large snow drifts that close roads and driveways, isolate farmsteads and increase snowplowing. Many of these drifting problems happen in the same place year after year. Although there are no foolproof methods of wind and snow control, properly designed and maintained snow fences can reduce or eliminate these problem areas. This publication discusses the benefits of snow fences, then examines the types used by the Iowa Department of Transportation. Finally, it provides information about how individuals can get involved in the DOT's Cooperative Snow Fence Program.

Iowa Department of Transportation. (n.d.). Living snow fence pilot project – Pocahontas County, Iowa. Ames, IA.

Summary: This short paper discusses the planting of two LSF planted in Pocahontas County, Iowa through cooperation with the Iowa Department of Transportation and the Pocahontas County Conservation Board. The snow fences consist of prairie grasses, forbes and flowers that are planted near state highways. These snow fences were planted as pilot projects in hopes of planting more living snow fences.

Kansas Forest Service, Kansas State University, Manhattan, KS. (2006, Jan.). Living Snowfences in Kansas. 18 May 2009 Retrieved from <http://www.oznet.ksu.edu/library/FORST2/L744.PDF>

Summary: This brochure outlines information about LSF in Kansas. It describes how the snow fences should be designed with suggestions of trees and shrubs to use. There are also diagrams of living snow fence designs, and there is information on obtaining assistance from the Kansas Forest Service in designing a snow fence.

Kuhn, G., D.P. Hanley and K.R. Gehrlinger. (2009). Davenport living snowfence demonstration: five-year update. *Northwest Science* 83(2), 163-168. Retrieved from BioOne. Syracuse University, Syracuse, NY. 12 May 2009 <http://www.bioone.org/>

Abstract: Snowfences are specialized windbreaks that divert drifting snow so it will accumulate in a predictable location. They are used commonly in areas with significant snowfall such as the Great Plains and upper mid-west, but are very uncommon in eastern Washington.

The purpose of this planting was to display establishment and initial growth in this portion of the country using technologies developed elsewhere. Snowfence demonstrations in southeastern Idaho and a small-scale dry land test plantings near Ritzville, Washington led to an interagency snowfence demonstration project north of Davenport, Washington. The project demonstrated new establishment technology and the value of living snowfences in this dry cropland region.

Sixteen snowdrift sites in Lincoln County were identified by road maintenance personnel from the Washington State Department of Transportation. In April 2003, we planted 532 trees and installed fabric mulch on four 268-meter long rows at the selected demonstration site. While the project's primary purpose was to demonstrate feasibility, the trees' yearly growth was also documented.

After five years tree height, crown width, and survival rates (100%) were greater than expected, suggesting that living snowfences can be successfully established in this area of the country. Also after five years, the snowfence started to catch drifting snow. The successful establishment and growth of this demonstration planting resulted in living snowfence demonstrations near Anatone, Washington and Athena, Oregon. Landowners and professionals working with landowners were encouraged to incorporate windbreaks into their conservation measures.

McLawnhorn, N. (2003, Apr. 1). Snowdrift Control. Transportation Synthesis Report Wisconsin Department of Transportation.

Summary: This document summarizes living snow fence programs in states other than Wisconsin and serves as an aid to the state of Wisconsin for developing their own program. It also summarizes programs and agencies involved in other methods of snow control such as issues with causeways and planning of highways. There is contact information for each of the programs and agencies.

Memorandum of understanding. (n.d.). Living Snow Fence Partnership Program. 13 May 2009 Retrieved from <http://www.forestry.iastate.edu/publications/MOUsnowfence.pdf>

Summary: This document outlines the plan for the Living Snow Fence Partnership Program that was proposed several years ago. This plan involves the US Department of Agriculture – Farm Service Agency, the Continuous Conservation Reserve Program, the Minnesota Department of Transportation, the Minnesota Association of Soil and Water Conservation Districts, and the US Department of Agriculture – Natural Resources Conservation Service. The document lists benefits of living snow fences, the logistics of the proposed program, parties involved, the goals of the program and the roles each agency will perform.

New York State Department of Transportation, Vegetation and Environmental Programs Section, Office of Transportation Maintenance. (2008, Dec.). Green and Blue Highways Initiative: Report for State Fiscal Year 2007-8. 18 May 2009 Retrieved from [https://www.nysdot.gov/divisions/operating/oom/transportation-maintenance/repository/Green and Blue Highways Report%202007-8-small.pdf](https://www.nysdot.gov/divisions/operating/oom/transportation-maintenance/repository/Green%20and%20Blue%20Highways%20Report%202007-8-small.pdf)

Summary: This report describes a project undertaken in New York State to improve Green and Blue Highways by improving vegetation along the roadways. These improvements included planting living snow fences.

Summary of SHRP research and economic benefits of snow and ice control. (1997, Dec.). Road Savers, U.S. Department of Transportation, Federal Highway Administration.

Abstract: In 1995, a project was initiated to assess the costs versus benefits of the Strategic Highway Research Program (SHRP). Information was collected from State and local highway agencies on their experiences with the SHRP products, and this information was used as the basis for an economic analysis of the costs and benefits of the program and its products. This report summarizes the preliminary findings of an economic analysis conducted by the Texas Transportation Institute. It also describes the snow and ice control technologies developed under SHRP and the experiences of highway agencies that have used them. In addition, it summarizes the objectives of the research conducted under SHRP on snow and ice control, and outlines the work by the Federal Highway Administration to refine the products and encourage their adoption.

Tabler, R.D. (1973). Snow fences improve highway safety. *Public Works* 104(8), 74-75. Retrieved from Scopus. Elsevier. 14 May 2009 <http://www.scopus.com/>

Abstract: Innovations in fence design and performance of the new fence systems in southwest Wyoming are described. The results have led the Wyoming Highway Department to use the methods and criteria to design an additional 40,000 feet of snow fence for second-priority sites, including those where poor visibility, rather than snow accumulation, is the principal problem. USDA Conservation Reserve Program. (n.d.). Living snow fence [brochure]. Iowa.

Summary: This brochure outlines how landowners can apply for the cost-share living snow fence program which is part of the Conservation Reserve Program of the USDA. Purposes of LSF and a design example are given as well.

Windbreak technology for wild blueberry fields. (1996). Department of Agriculture and Aquaculture, New Brunswick Government. 19 May 2009 Retrieved from <http://www.gnb.ca/0171/10/0171100001-e.asp>

Summary: This fact sheet describes how to design a windbreak for blueberry fields. It discusses how the windbreak is useful in trapping snow to reduce damage to the blueberry plants; and there is a chart of trees and their characteristics that can be used in the suggested windbreaks. While this is not directly related to roads, it has useful information on how New Brunswick has developed windbreaks.

Wyatt, G.J. (1999). CRP snow fence (preventing snow drifting). *Successful Farming*. 97(3), 36. ProQuest Research Library. ProQuest. Syracuse University, Syracuse, NY. 13 May 2009 Retrieved from <http://proquest.umi.com/>

Abstract: Living snow fences, the planting of shrubs and trees specifically designed and planted in fields that will trip the snow before it can form drifts on roadways, are discussed.

Research

This category only contains a few articles, but they center around scientific research on windbreaks and living snow fences. Aspects such as the optical porosity of plants used, the aerodynamic structure of a windbreak, and wind speed are discussed.

Loeffler, A.E., A.M. Gordon, and T.J. Gillespie. (1992). Optical porosity and windspeed reduction by coniferous windbreaks in southern Ontario. *Agroforestry Systems* 17, 119-133. Retrieved from Scopus. Elsevier. Syracuse University, Syracuse, NY. 13 May 2009
<http://www.scopus.com/>

Abstract: Relative windspeed reduction was measured behind nine relatively narrow, homogeneous windbreaks in southern Ontario, Canada to assess whether any characteristics of the windspeed reduction curve could be predicted from optical porosity. The latter was determined for each windbreak using high contrast black and white photographic silhouettes on a computer digitizing system. Minimum windspeeds behind the windbreaks ranged from 29 to 71% of open windspeed; these minima were located 2 to 6 multiples of windbreak height away from the windbreak. Optical porosities of the bottom half of the windbreak ranged from 0 to 31%. Multiple regression of the shelter parameters (location and value of minimum relative windspeed) on the independent variables (optical porosity, open windspeed, surface roughness, approaching wind direction relative to the windbreak, average tree diameter and average tree spacing) showed that the minimum relative windspeed could be predicted from the optical porosity of the bottom half of the windbreak. The results suggest that optical porosity can be used to predict minimum relative windspeeds and may therefore be useful as a guide in the field evaluation of windbreaks.

Nixon, W.A., M. Davison, and G. Kochumman. (2006). Living snow fences. Iowa Highway Research Board Project Technical Report #460. University of Iowa. 12 May 2009 Retrieved from <http://publications.iowa.gov/4871/1/tr460.pdf>

Abstract: Blowing snow can cause significant problems for mobility and safety during winter weather in three distinct ways. It may drift onto the road, thus requiring almost continuous plowing while the wind is blowing (which may occur when a given winter storm is over). Snow may drift onto wet pavement (perhaps caused by ice control chemicals) and dilute out the chemicals on the road, creating ice on the road. And sufficient blowing snow can cause a major deterioration in visibility on the road, a factor which has been shown to be significant in winter crashes. The problem of blowing snow can be very effectively addressed by creating a snow storage device upwind of the road that requires protection from snow drifting. Typically, these storage devices are fences. Extensive design guidance exists for the required height and placement of such fences for a given annual snowfall and given local topography. However, the design information on the placement of LSF is less complete. The purpose of this report is to present the results of three seasons of study on using standing corn as snow fences. In addition, the experience of using switch grass as a snow storage medium is also presented. On the basis of these experimental data, a design

guide has been developed that makes use of the somewhat unique snow storage characteristics of standing corn snow fences. The results of the field tests on using standing corn showed that multiple rows of standing corn store snow rather differently than a traditional wooden snow fence. Specifically, while a traditional fence stores most of the snow downwind from the fence (and thus must be placed a significant distance upwind of the road to be protected, specifically at least 35 times the snow fence height) rows of standing corn store the majority of the snow within the rows. Results from the three winters of testing show that the standing snow fences can store as much snow within the rows of standing corn as a traditional fence of typical height for operation in Iowa (4 to 6 feet) can store. This finding is significant because it means that the snow fences can be placed at the edge of the farmer's field closest to the road, and still be effective. This is typically much more convenient for the farmer and thus may mean that more farmers would be willing to participate in a program that uses standing corn than in traditional programs. On the basis of the experimental data, design guidance for the use of standing corn as a snow storage device in Iowa is given in the report. Specifically, it is recommended that if the fetch in a location to be protected is less than 5,000 feet, then 16 rows of standing corn should be used, at the edge of the field adjacent to the right of way. If the fetch is greater than 5,000 feet, then 24 rows of standing corn should be used. This is based on a row spacing of 22 inches. Further, it should be noted that these design recommendations are ONLY for the State of Iowa. Other states of course have different winter weather and without extensive further study, it cannot be said that these guidelines would be effective in other locations with other winter conditions.

Zhou, X.H., et.al. (2004). Three-dimensional aerodynamic structure of a tree shelterbelt: definition, characterization, and working models. *Agroforestry Systems* 63, 133-147. Retrieved from Scopus. Elsevier. Syracuse University, Syracuse, NY. 13 May 2009 <http://www.scopus.com/>

Abstract: In order to make recommendations to landowners with regard to the design and management of tree shelterbelts, it is necessary to understand and predict the wind flow patterns associated with shelterbelt structure. A structural description is a prerequisite for any prediction of wind flow. Optical porosity (percentage of open spaces on the side view of a shelterbelt) has been used as a structural descriptor of a shelterbelt; however, it is a 2-dimensional measure unable to fully represent the aerodynamic influence of a tree shelterbelt. Based on numerous studies observing the wind fields associated with shelterbelt structure, the overall aerodynamic structure of a tree shelterbelt in three dimensions is defined by its external structural characteristics (length, height, width, and cross-sectional shape) and by its internal structural components (amounts and arrangements of vegetative surface area and volume, and geometric shape of individual vegetative elements). In order to associate the defined structure with wind speed, turbulent stress, and pressure, it is characterized using two structural descriptors the spatial functions of vegetative surface area density (vegetative surface area per unit canopy volume) and cubic density (vegetative volume per unit canopy volume). For field estimation, the two structural descriptors are expressed in three dimensions using two working models in terms of 1- or 2- dimensional sub-functions capable of being defined with field measurements. This paper discusses the rationale behind the definition, characterization, and working models for the 3-dimensional aerodynamic structure of a tree shelterbelt.

A Summary of Existing Living Snow Fence Programs in North America

Prepared by Ruth Williamson and Timothy A. Volk

SUNY – ESF, Syracuse, NY 13210

Completed as part of Task 1-A of the New York State Department of Transportation Research Project C-06-09 “Designing, Developing, and Implementing a Living Snow Fence Program for New York State” (PIN R021.13.881, Research Consortium Contract: No. C030506)

August 2009



Task 1-A: A Summary of Living Snow Fence Programs in North America

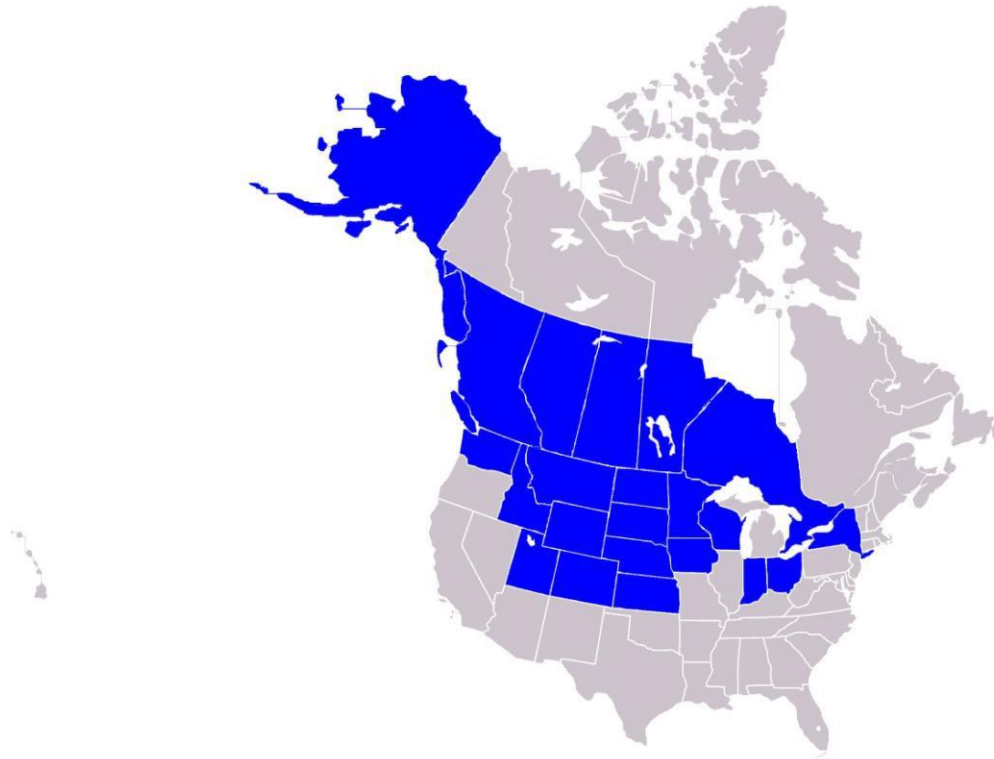


Figure 1: Location of states and provinces that have, or have previously had a program or part of a program focused on living snow fences.

Table 1: Matrix of characteristics of living snow fence programs for different states and provinces in North

	Landowner Assistance	Financial Incentives	Active as of 2009	Design Info	Seedlings Provided or Available	Focus on Living Snow Fences	Conservation Forestry or Roadside Landscape Projects	Organization
Alaska	Y	Y	Y	Y	?	N	Both	Alaska Division of
Colorado	N	Y	Y	?	Y	Y	Conservation Forestry	Colorado State Forest Service
Idaho	Y	Y	Y	?	?	N	Both	Idaho Departments of Transportation and Land
Indiana	Y	Y	Y	Y	Y	Y	Conservation Forestry	USDA NRCS CRP
Iowa	Y	Y	Y	Y	N	Y	Conservation Forestry	IDOT & USDA NRCS CRP
Kansas	Y	Y	N	Y	Y	N	Conservation Forestry	Kansas Forest Service

Minnesota	Y	Y	Y	Y	?	Y	Neither	Minnesota DOT
Montana	N	N	Y	Y	Y	N	Conservation Forestry	DNRC Forestry Division
Nebraska	Y	Y	N	?	?	Y	Conservation Forestry	CRP; National Agroforestry Center; Department of Roads, Game and Parks
New York+			Y			Y		NYS Thruway Authority, SUNY-ESF, & NYSDOT
North Dakota	Y	Y	Y	?	?	Y	Neither	North Dakota State Forest
Ohio	Y	Y	Y	Y	Y	N	Both	ODOT, ODNR Division of Forestry, USDA NRCS, SWCD, FSA
South Dakota	Y	Y	Y	Y	?	Y	Neither	South Dakota Department of Agriculture
Utah	Y	Y	Y	Y	Y	N	Conservation Forestry	USU Extension, Utah Division of Forestry Fire and State Lands, NRCS
Washington+			?	X		Y	Roadside Landscape	WSDOT & NRCS
Wisconsin	Y	Y	Y	Y	Y	N	Conservation Forestry	DNR Division of Forestry, NRCS
Wyoming	Y	Y	Y	Y	?	Y	Neither	Wyoming State Forestry Division, WYDOT, & Wyoming Association of Conservation Districts
Alberta	N	Y	Y	Y	Y	N	Conservation Forestry	AAFC-PFRA (?)
British Columbia	N	Y	Y	Y	Y	N	Conservation Forestry	AAFC-PFRA
Manitoba	N	Y	Y	Y	Y	N	Conservation Forestry	AAFC-PFRA

Ontario+	Y	Y	Y	Y	?	Y	?	Region of Peel Public Works & University of Toronto's Faculty of
Saskatchewan	N	Y	Y	Y	Y	N	Conservation Forestry	AAFC-PFRA

This matrix compiles characteristics of living snow fence programs by state/province. In this matrix, a Y indicates that the state or province has the listed type of program or item (landowner assistance, financial incentives, etc.), and an N indicates the state or province does not have the listed item. A question mark denotes that information on the particular listed item is unknown or inaccessible for the state or province.

If the state or province's program is not specific to planting living snow fences, often the program is more focused on conservation forestry or improving roadside landscape. Therefore, the matrix notes whether a program focuses on conservation forestry or roadside landscape when it does not focus on living snow fences. Sometimes a program has focus on all three aspects and sometimes the program may not be specific to living snow fences, but the efforts for conservation forestry and/or roadside landscape include some planting of living snow fences.

The "Information Provided on Design" item/category specifies whether the state or province provides information to landowners on how to design and/or plant living snow fences.

* Nebraska does not have an active living snow fence program anymore; however, information was gathered about the program when it was active.

+Washington and Ontario appear to have living snow fence programs, but contacting the state and province about their programs was unsuccessful for gathering current information. New York has a developing living snow fence program, making inputting information in this matrix difficult at this time.

United States

Alaska:

"Community Forestry Grants – 2008." Alaska Community Forestry Program. (2008). 18 May 2009
<http://forestry.alaska.gov/community/08GrantProposal.doc>

Summary: This brochure outlines how applicants can apply for grant money to "solve community problems" using community forestry programs.

Contact: Alaska Division of Forestry Community Forestry Program

550 W. Seventh Avenue, Suite 1450

Anchorage, Alaska 99501-3566 Patricia Joyner, Program Coordinator 907-269-8465

patricia.joyner@alaska.gov

Telephone Interview: In 2009, the program is offering one grant for the cities of Ketchikan and Sitka for inventory and management of tree plantings. There isn't much of a state-wide living snow fence program; however some of the trees have been used to create living snow fences. Currently, the program encourages and educates people in communities to properly plant trees in cities and parks and aid people in building windbreaks.

This program has found it best to offer hands-on help, to actually be with the people while planting trees to show them exactly how to do it correctly. They have also produced publications explaining the best practices of tree planting and management and benefits of trees and windbreaks; these publications are helpful to people. It has also been beneficial to work with partners, such as the

Forest Service and companies who provide trees. Working with people who can pass on information and train others has also worked well in the success of the program. This program, like many others, could use more money in their budget and they would like to pursue funds from the state. It has been found that training community leaders to plant trees and take advantage of the program correctly is important because the program relies on the leaders of each community to utilize the program and communicate it to others in the community. Also, the program would like to try using webinars and seminars to train people in the planting and management of trees.

Colorado:

“Annual Report.” Colorado State Forest Service, Woodland Park District. (2007). 14 May 2009 http://csfs.colostate.edu/pages/documents/WoodlandPark_District_2007Annual_Report.pdf

Contact: Colorado State Forest Service Greg Sundstrom

5060 Campus Delivery

Fort Collins, CO 80523-5060 970-491-5342

970-491-7736 FAX

Summary: The Colorado State Forest Service Trees for Conservation Program “provides affordable tree and shrub seedlings” to landowners that can be planted for conservation purposes such as living snow fences.

Telephone Interview: Colorado’s living snow fence program is no longer current on a state-wide level. However, over the course of the state-wide program over 200 LSF were planted and have been maintained. Many of those LSF were planted as demo projects to introduce new technology such as drip systems and weed barrier materials.

Currently, LSF are planted on the local level through the conservation districts. Often these local programs have cost-share relationships with the Forest Service, DOT and other agencies to plant the snow fences. When the state-wide living snow fence program was active, coordination at the local level was very important. Cooperation with all the contributing entities (DOT, Forest Service, etc.) involved was crucial. Also, the maintenance of the LSF after they were planted was very important to their survival and success; the maintenance of LSF in Colorado was successful and most of those snow fences are still working.

Promoting more LSF would have helped the living snow fence program in Colorado; and, more specifically, promoting the benefits of LSF to stakeholders. They are not just for snow control, but also provide wildlife habitat, protection from wind, and aid in a clean environment.

Idaho:

“Idaho Department of Lands Announces Community Transportation Enhancement Grant.” Urban and Community Forestry Program. 2007. 15 May 2009 http://www.idl.idaho.gov/bureau/community_forestry/grants/cte_grant_pgm/cte2007/cte2007-08_announcement_itr.pdf

Contact: Coeur d’Alene Staff Headquarters Urban and Community Forestry Program 3780

Industrial Avenue South

Coeur d’Alene, ID 83815

Joyce S. Jowdy – (208) 666-8622 communitytrees@idl.idaho.gov

Summary: The information sheet listed above contains information about the Community Transportation Enhancement Grant in Idaho, which provides grant money to city, county and tribal governments for landscaping and building LSF and windbreaks. The grant is funded by the Idaho

Department of Transportation and administered by the Idaho Department of Lands and the Idaho Community Forestry Advisory Council.

Telephone Interview: The Urban and Community Forestry Program is still current, and this is their second year of providing grant money. This program provides up to \$30,000 grants to communities to aid their enhancement of transportation corridors (such as bikeways, highways, business districts, and railways). The funds come from the Idaho Department of Transportation, but the program is administered by the Idaho Department of Lands. In 2009, there is \$172,000 available. The program aims to educate communities in using the right plant species for each purpose and promote the utilization of the functional aspect, rather than the aesthetic aspect, of the trees; for example, using trees as snow fences, noise barriers, and windbreaks.

The program has found that having individual assistance in each project to be helpful, such as having foresters work directly with the communities. These individuals/foresters make sure the community is thinking of the useful characteristics of the trees, give technical assistance, extra guidance and follow-up.

Keeping the new tree planting projects maintained is the biggest concern and usually there is a lack of funding, staff, or expertise for maintenance. Idaho's program recognizes the importance of encouraging the proper planting of trees because often the trees are not planted correctly and the trees do not last. Idaho also suggests that a successful program should be sure to partner with the DOT and other non-profit entities and make sure that proper education is given for proper planting of trees.

Indiana:

“CRP Practice CP17A Living Snow Fence.” USDA Natural Resources Conservation Service.

March 2007. 18 May 2009 <http://www.in.nrcs.usda.gov/programs/>

CRP/07%20program%20sheets/IN%20CP17A%20Program%20Sheet%20vJan%201-0.doc

Contact: NRCS - Indiana State Office Ken Collins

6013 Lakeside Boulevard

Indianapolis, Indiana 46278-2933

Phone: (317) 290-3200 ext. 356

FAX: (317) 290-3225

Summary: The Conservation Reserve Program of the USDA NRCS provides fact sheets on many projects, including LSF and shelterbelts, for Indiana, as well as other states.

Telephone Interview: Currently, Indiana's living snow fence program relies on the Conservation Reserve Program (CRP), which is funded by the Commodity Credit Corporation, administered by the Farm Service Agency, and the NRCS provides technical and conservation planning.

Landowners use this program primarily for windbreaks, and often the windbreaks serve as living snow fences. Indiana also uses the Conservation Reserve Enhancement Program (CREP), which is a part of CRP and pays landowners fifty-eight cents per foot of windbreak as an incentive.

Landowners can purchase trees from the state nursery and are responsible for planting them themselves. Sometimes landowners will hire professionals to help in planting the trees and some counties rent tree planting machines to landowners. The program provides job sheets for different conservation plantings that give information on proper planting, maintenance of trees, and provide a guide to choosing the appropriate trees. The program has been successful in promoting the program to landowners. The state nursery is very essential in the success of the program because

the landowners have a great source for trees. Also, the landowners rely on the local agencies for help in using the program and this is helpful so that the landowners do not have to go to the state agencies in Indianapolis or Chicago. One thing that could be helpful for the program in Indiana is getting landowners to work together cooperatively so the benefits of windbreaks are fully realized. For example, if farmer A plants a windbreak, it might be beneficial if farmer B down the road also plants a windbreak so that the farmer A's windbreak is actually more useful. Operation of the program would also be more efficient when landowners work together and the local/county agencies also work together to get jobs done.

Iowa:

“Iowa’s Cooperative Snow Fence Program.” Iowa Department of Transportation, July 2002. 13

May 2009 <http://www.iowadot.gov/maintenance/internetpages/pdf/snowfence%20booklet.pdf>

Contact: Local DOT maintenance office, info found at <http://www.iowadot.gov/> Iowa Department of Transportation Maintenance

Dennis Burkheimer 515-239-1355

Summary: The Iowa Department of Transportation started the Cooperative Snow Fence Program in 2002 to create agreements with landowners to build LSF on private land.

Telephone Interview: The Cooperative Snow Fence Program in Iowa is still operational, although it is not very active. The program is collaboration between the DOT and the USDA Farm Service Agency CRP programs. Landowners can set aside acreage for planting of LSF under CRP. The Cooperative Snow Fence Program also builds permanent or temporary wood or plastic snow fences. The LSF are generally a couple of rows of native shrubs and grasses, as landowners/farmers do not want trees with deep root systems planted.

Landowners are reimbursed for the cost of the shrubs and grasses. Iowa DOT maintenance forces will do the planting. The most active part of the program buys, from farmers, eight to ten rows of standing corn at fifty cents per bushel over the current market rate at the end of harvest time to act as living snow fences. Cooperation of landowners has been crucial in success of the program; they see the benefits of having a living snow fence and let others know.

Funding is always a difficulty, especially as the price of corn fluctuates so much and the majority of the program is buying standing rows of corn. The program would like to see another source of funding to give more incentive to landowners to plant living snow fences. Also, it often is difficult to find enough people to plant the shrubs and grasses.

Kansas:

“Conservation Tree Planting Program.” Kansas Forest Service. 5 May 2009. 14 May 2009

<http://www.kansasforests.org/conservation/index.shtml>

Living Snowfences in Kansas. 2006. Kansas Forest Service. 11 May 2009

<http://www.oznet.ksu.edu/library/FORST2/L744.PDF>

Contact: Jim Strine

Kansas Forest Service

District Forester - Northwest District Champion Tree Program Coordinator 1232 240th Avenue
Hays, KS 67601

785-625-3425 ex. 220

www.kansasforests.org

Summary: The Kansas Forest Service's Conservation Tree Planting Program offers seedlings for planting in conservation efforts such as windbreaks. The Kansas Department of Transportation has helped in planting living snow fences; however, there does not appear to be a specific program just for LSF at this time. A brochure from the Kansas Forest Service in 2006 outlines information about LSF in Kansas at that time. It describes how the snow fences should be designed with suggestions of trees and shrubs to use. There are also diagrams of living snow fence designs. The brochure gives information on obtaining assistance from the Kansas Forest Service in designing a snow fence.

Telephone Interview: The Conservation Tree Planting Program is still current, but not as far as promoting or planting living snow fences. The program was successful for a little while in planting living snow fences. Currently the program offers tree and shrub seedlings for planting in conservation efforts, particularly for farmstead and livestock windbreaks (which do protect from snow) and for providing wildlife habitat. These efforts are cost-shared with Wildlife and Parks, KDOT, and NRCS. The program has done well in contacting landowners about planting trees for windbreaks and living snow fences. It also has had success in paying for the cost of the trees, planting them for the landowner, and installing weed barriers to help in the maintenance of the windbreaks. This program realized that it would be more successful if the DOT was more involved because the DOT has money and knows the areas that need living snow fences. If the DOT is not interested in snow fence efforts of this program, then it is an uphill battle in promoting and installing them.

Minnesota:

Living Snow Fences. 2009. Minnesota Department of Transportation. 11 May 2009

<http://www.dot.state.mn.us/environment/livingsnowfence/>

Contact: Minnesota Department of Transportation Dan Gullickson
(651)366-3610

Summary: The Minnesota Department of Transportation LSF program website contains information on the importance of snow fences and descriptions of different kinds of structural and living snow fences. There are four types of LSF described including: twin shrub row, deciduous tree windbreak, community shelterbelt, and grassland nesting bird component. A link to a plant selector for determining which plants would be best for snow fences is provided, although the link is broken. There are links to photographs of LSF and contact information, and information in joining the program.

Telephone Interview: MnDOT partners with the USDA Conservation Reserve Program to plant living snow fences. Currently, landowners receive money for agreeing to have a snow fence planted on their property as part of the CRP process.

There are about five plantings per year on state highways, with many other plantings along county roads. Sometimes, contractors are hired to plant the trees. In 2009, the program has been using some economic stimulus money for plantings. The program has continually been making improvements and looking to better promote the program. Last year they took an inventory of over 4,000 problem sites on roadways and has been working towards improving them. Research over the next year includes: 1) Assessing farmer/landowner costs to take farmland and convert it into planting snow fences. Some of the costs are hand pulling weeds and giving up land used for crops. 2) Evaluating MnDOT operating costs; keeping the roads open is the goal. 3) Reviewing safety of

roadways in effort to reduce accidents. The findings of this research should tell whether the program is working well and what steps can be taken to improve the program. So far, it has been noted that the shrubs in the LSF catch the most snow.

There is a need for more funding to tackle improvement of problem areas; as of now, only five to ten of the 4,000 problem sites are being resolved every year. Non-severe winters do not help people remember how important LSF and proper snow control are. This hinders the progress of the program. Also, the program has found that there needs to be better communication with private landowners and more partnering with county and local USDA offices. A local contact would be beneficial to promoting the program. Minnesota suggests that for a successful living snow fence program, there is a need for good data on how to best design living snow fences. The state suggests looking at its Memorandum of Understanding, which outlines how Minnesota developed partnerships with the DOT as this will aid other states in developing essential partnerships (this document is listed in the literature review). In addition, Minnesota suggests that a living snow fence program needs to have a decentralized approach for landowners, yet there needs to be a centralized place for contact and information.

Montana:

“Suitable Uses for MCSN Seedlings.” Montana Department of Natural Resources and Conservation Forestry Division. 2009. 15 May 2009 <http://dnrc.mt.gov/forestry/Nursery/suitable.asp>

Contact: Department of Natural Resources and Conservation Conservation Seedling Nursery
John Justin

PO Box 201601,
Helena MT 59620
406-542-4327

Summary: The Montana Conservation Seedling Nursery of the Department of Natural Resources and Conservation Forestry Division produces and provides seedlings for conservation practices such as LSF and windbreaks.

Telephone Interview: The program is still providing information on proper planting and selling seedlings to landowners for planting windbreaks and shelterbelts. However, it does not provide actual assistance in tree planting. Sometimes, landowners will plant LSF to help provide access to their property when it snows. However, the nursery doesn't keep track of what specifically the landowners use the trees for, just so long as they are used for conservation purposes. About 800 private landowners per year buy seedlings from the Conservation Seedling Nursery. If a landowner needs actual assistance in planting the trees, local conservation districts are available to help landowners properly plant the seedlings.

The Conservation Seedling Nursery has provided quality seedlings that survive after planting and the program is fully funded through the sale of the seedlings. The program has been successful due to a close relationship with local conservation districts who will promote the seedling program to landowners. There isn't much the program would do differently, although sometimes being self-funded is limiting and if it was subsidized in some way, the program would expand more.

Nebraska:

Forest Land Enhancement Program. (n.d.). 16 July 2009
<http://www.nfs.unl.edu/documents/flep%20brochure2.pdf>

Contact:

Forest Stewardship Program Coordinator 109 Plant Industry Bldg., UNL
Lincoln, NE 68583-0815

Phone: 402-472-5822

National Agroforestry Center

Richard Straight – Referred by John Hinnners 402-437-5178

Roadway Design Manual. Nebraska Department of Roads. (2006). 14 May 2009

<http://www.dor.state.ne.us/roadway-design/pdfs/rwydesignman.pdf>

Summary: LSF in Nebraska are planted through a cost-share program through the Nebraska Forest Service and the Forest Land Enhancement Program (FLEP) of the USDA. This cost-share program helps private landowners improve forest land and plant trees for conservation purposes. The above cited brochure gives details on the program and how a landowner would go about participating in the program. The Nebraska Department of Roads (NDOR) discusses the possibility of using building LSF along roadways in the Roadway Design Manual, but there does not appear to be a specific program with NDOR.

Telephone Interview: The program is not active, due to a lack of funding. When the program was active in the early 1980s and again in the late 1990s, it was primarily a cost-share program for planting trees as living snow fences. The Department of Roads, Game and Parks, and CRP each contributed funds to landowners for planting living snow fences. The program sometimes put in a feed plot for wildlife because the landowners were concerned about preserving wildlife. Many of the snow fences were planted on grassland or pasture land because landowners saw their farmland as too valuable to give up for living snow fences. The program is not currently active, largely because the funding agencies need to allocate their funds to other pressing matters. The program needs funds from several agencies (not just one) to work. Also, snow fences can be an imposition to landowners because they are hard to manage when there is no money to maintain the snow fences. The program was successful in that there was cooperation with landowners and local technicians in the soil conservation district and NRCS offices. The landowners knew these technicians were credible and had established trust with them, and so the benefits of LSF were recognized. Because many of the snow fences were planted on pastureland, a fence needed to be placed around the trees to keep the livestock out; this fencing was completely paid for by the program and helped out the landowners. The landowners were also concerned with protecting wildlife and this was often a great incentive to planting living snow fences.

One problem that was recognized was the Department of Roads required a long-term lease on the land to be planted and this lease was very expensive. The lease was needed to ensure landowners would not remove the trees once planted. By having to purchase vegetation and a lease, the available money in the program could not go as far.

New York:

“Ecology – Living Snow Fence Program.” New York State Thruway Authority. 14 May 2009

<http://www.nysthruway.gov/environmental/ecology.html>

“Living Snow Fences.” New York State Department of Transportation. 2008. 14 May 2009

https://www.nysdot.gov/divisions/engineering/design/landscape/trees/rs_liv_sn_fence

“Willow Living Snow Fence.” Cooperative Conservation America. 14 May 2009. 14 May 2009

<http://www.cooperativeconservation.org/viewproject.asp?pid=817>

Contact for Willow Living Snow Fence: Mary O’Reilly

Environmental Specialist II NYS DOT
44 Hawley Street
Binghamton, NY 13901
607-721-8138
mbrophy@dot.state.ny.us Tim Volk
Senior Research Associate SUNY ESF
345 Illick Hall 1 Forestry Drive SUNY ESF Syracuse, NY 13210
315-470-6774
tavolk@esf.edu

Summary: The New York State Thruway Authority website gives a brief description of the first project in the Living Snow Fence Program in the Buffalo area in July 2006. This project was possible through collaboration with the New York State Thruway Authority and SUNY-ESF. The Living Snow Fence project in New York involves the New York State Department of Transportation and the SUNY-ESF. The website contains information on the projects progress and contact information. The New York State Department of Transportation Office of Design – Landscape Architecture has started planting LSF to help prevent snowdrifts on highways. This program does not seem to have collaboration with the NYS Thruway Authority or SUNY-ESF.

North Dakota:

“Living Snow Fence.” n.d. North Dakota State Forest Service. 11 May 2009
http://www.ndsu.nodak.edu/forests/service/sustain/living_sf.htm

Contact: Tom Claeys

Forestry and Fire Management Assistance Team Leader (701) 328-9945

Thomas.Claeys@ndsu.edu

Summary: Simple website outlining the need for and benefits of LSF in North Dakota. A link to a form for requesting a grant and permission to build a snow fence is provided.

Telephone Interview: The living snow fence program in North Dakota started in 1997 as a cost-share program. There have been over 500 LSF planted and there are LSF in every county. The program also partners with the NRCS and the Forest Service.

Currently, the program has an incentive/cost-share program for private and public landowners to build LSF to protect public roads.

Utilizing local natural resource professionals and involving local soil conservation districts has been key to the success of the program because they are able to work with the landowners and help plant the snow fences. Also, learning from what adjacent states have done has aided in improving the program. So far, the program has been able to provide 100 percent of the cost of the trees for the landowners and has found that installing weed barriers greatly increases survival of the trees. Timing of projects is always an obstacle. For example, land must be surveyed for culture resources before a living snow fence can be planted. This takes a great deal of time and there needs to be a way to streamline the process.

Ohio:

“Roadside Safety Landscaping Guidelines.” Ohio Department of Transportation. 2006. 18 May 2009 http://www.dot.state.oh.us/policy/AestheticDesign/Documents/ref_landscaping_jan06.pdf

Contact: The Ohio Department of Transportation 1980 West Broad Street
Columbus Ohio, 43223

“Northwest Ohio Windbreak Program.” Ohio Department of Natural Resources Division of Forestry. 2008. 18 May 2009 <http://www.ohiodnr.com/tabid/5290/Default.aspx>

Contact: Division of Forestry, Service Forester Brian Riley
419-429-8315

Summary: The Ohio Department of Transportation has a landscaping program that takes into account planting trees for snow fences. Also, the Department of Natural Resources Division of Forestry has a windbreak program that is more focused on preserving wildlife and curbing soil erosion than it is on creating living snow fences. However, the windbreak program has published a thorough windbreak guide with information on designing windbreaks and descriptions of plants to use.

Telephone Interview: The Northwest Ohio Windbreak Program began in 1977 and is still current. However, it now focuses on planting windbreaks for preventing soil erosion, presenting aesthetics, and providing wildlife habitat in the seventeen county northwest region of Ohio. While the purpose of this program is not specifically to plant living snow fences, often the windbreaks will catch a certain amount of snow as an added benefit. The program plants about 360,000 row feet of windbreaks every year, which works out to about sixty-eight miles and about twenty to thirty windbreaks every year. The program is a turn-key program that works with partner groups such as local NRCS and FSA offices, as well as the Division of Wildlife to plant windbreaks in the spring. Landowners receive thirty cents per row foot of windbreak planted. The program pays for and provides labor for planting the windbreaks, replacing plants and applying herbicide. The program also selects the plant species to be planted at each site. Windbreaks can have up to six rows and at least one row must be made up of evergreens.

Because the program has been operating for over thirty years, people see how nice the windbreaks look and they are likely to plant more. The program has received good feedback from landowners and the success of the program has largely been promoted by word of mouth from satisfied landowners. The program adjusts as problems come up. Sometimes the plant species (there are thirteen different species used in the program) are adjusted based on site, soil conditions, and growing requirements. There isn't much the program would do differently; it is a very successful program.

South Dakota:

The Living Snow Fence Program in South Dakota. 2004. South Dakota Department of Agriculture. 11 May 2009 <http://www.state.sd.us/doa/forestry/publications/LSF%20Brochure.pdf>

Contact: Office of the State Forester

South Dakota Department of Agriculture Resource Conservation & Forestry

John Hinnert

523 E. Capitol Avenue Pierre, SD 57501-3182

605-353-7187

Summary: The Living Snow Fence Program in South Dakota is funded by the South Dakota Department of Transportation and the South Dakota Department of Agriculture Division of Resource Conservation and Forestry. A brochure (link provided above) is available that describes LSF and how landowners in South Dakota may participate in the program.

Telephone Interview: In 2009, South Dakota's living snow fence program has had one contract for a living snow fence and two more are pending. The program started in 1986 as a part of the DOT and LSF were only planted on federal highways. In 2000, the Division of Resources Conservation and Forestry of the Department of Agriculture took management of the program and has since planted over 110 LSF near public roads. This program will draw up a design plan and provide technical service for the landowner to plant a snow fence. For South Dakota, planting LSF in a five row configuration of mostly shrubs with some mid- size and tall deciduous trees has worked well. The program is a cost-share one in which money is provided from the DOT for site preparation, planting of trees (which is done by the conservation districts), five years of maintenance, two years of replanting, 20% of the cost of trees, and the land is rented for ten years. The amount of money for each contract depends on an eligibility number calculated by the DOT. This program has had success due to promotion of the benefits of LSF and working with the DOT in finding the roads that have problems with snow. It has been important to have DOT engineers and superintendants on board and working with the program. Snow helps promote LSF and encouraging people to plant them, When there is heavy snow during a winter, people want a solution to snow-covered roads. Therefore, the program is often cyclical based on how much snow falls each year. Some problems that have occurred since the program started are: snow fences are planted too close to the road because landowners don't want to give up so much land, sometimes the trees planted are not compatible with soil type, the increasing number of non-resident landowners who do not see the need for planting LSF or shelterbelts limits planting of LSF in needed areas, and evergreen trees have not worked as well in windbreaks because a heavy snow will break them in half and then they are not able to re-sprout.

Utah:

Utah Forest Facts. 1998. Utah State University Extension. 15 May 2009 http://extension.usu.edu/forestry/Reading/Assets/PDFDocs/NR_FF/NRFF005.pdf

Contact: Mike Kuhns

USU Forestry Extension 5230 Old Main Hill Logan, UT 84322-5230

State of Utah Division of Forestry – Moab Office Natalie Conlin

435-259-3766

Summary: The fact sheet listed above gives an overview on the use of tree and shrub windbreaks. It describes the many benefits of windbreaks and goes over important aspects of windbreak design.

Telephone Interview: Utah does not have a program that is specific to LSF at this time. However, the Division of Forestry does provide advice and assistance to landowners who want to build windbreaks. Utah is split into six areas; each area has a state forester who helps landowners design windbreaks and find seedlings for planting. Utah used to have a state nursery that provided seedlings under the FLEP program, but now landowners are referred to local nurseries or Colorado and New Mexico state nurseries. The state foresters help landowners get cost-share assistance through the NRCS Environmental Quality Incentive Program that operates in many states. They also will provide free assistance in drawing up plans for windbreaks and suggest species for planting. Sometimes landowners will be partnered with local Boy Scout troops to help in the actual planting of trees. Usually, landowners build windbreaks for the protection from winds, but an added benefit is that they sometimes also function as living snow fences. The assistance program through the Division of Forestry is a free service for landowners and they appreciate the help very much. The program realizes that having a windbreak expert on staff would greatly help the success

of the program, but foresters can always refer landowners to NRCS personnel who are very knowledgeable.

Washington:

“Living Snow Fence.” USDA Natural Resources Conservation Service. March 2003. 18 May 2009 ftp://ftp-fc.sc.egov.usda.gov/WA/news/fact_sheet_pdf_files/living_snow_fence_fs.pdf
MacDonald, D.B. Measures, Markers and Milestones. Washington State Department of Transportation, March 2003. 18 May 2009 <http://www.wsdot.wa.gov/NR/rdonlyres/255D5A7C-932F-4C76-9944-D0576ED4C538/0/GrayNotebookMar03.pdf>

Contact: Gary Kuhn, Agroforester Western Office (509) 358-7946
kuhn@wsu.edu

Summary: The fact sheet from the Natural Resources Conservation Service listed above gives information on a living snow fence planted in Washington. The snow fence project is a partnership with the USDA National Agroforestry Center and Natural Resources Conservation Service, Lincoln County Conservation District, Washington Department of Fish and Wildlife, and the Washington State Department of Transportation. The publication from the Washington State Department of Transportation also describes a living snow fence that was planted along State Route 25.

Wisconsin:

Contact: DNR, Division of Forestry

Wisconsin State Nursery Program Griffith State Nursery

Jeremiah Auer

473 Griffith Avenue Wisconsin Rapids, WI 54494 (715) 424-3700

<http://www.dnr.state.wi.us/forestry/Nursery/>

Summary: Wisconsin has a program for planting windbreaks, which can also be used as living snow fences, that is managed by the Wisconsin Department of Natural Resources Division of Forestry and the Natural Resources Conservation Service.

Telephone Interview: The State Nursery Program sells trees to landowners for use in primarily reforestation and wildlife conservation projects, although many of the trees are used to plant windbreaks and living snow fences. Wisconsin also participates in EQIP, a program of the NRCS. The State Nursery has worked some with the Wisconsin Forest Landowner Grant Program which pays for half of the cost for planting windbreaks for eligible landowners.

The State Nursery Program provides trees to landowners in ten different packets of 300 seedlings. The energy packet is made up of conifers and is used mainly for windbreaks.

Landowners must buy at least 1,000 trees at a time. The program also provides technical assistance to landowners and information on proper planting techniques. Each county has a forester who helps landowners with planting if needed, and have tree planters for rent. Mr. Auer will go out to recently planted sites every summer to see how the trees are doing.

The State Nursery Program has in existence since 1932 and the trees that have been planted since then have been very successful. The state looks very nice with all the trees that have been planted through the program. The fact that the nursery will visit sites is important to assessing success of trees and plantings.

Conifers do very well in Wisconsin and it has been found that they are quite deer resistant. The program has also distributed many pamphlets on windbreaks to residents and school children to promote the usefulness of windbreaks. The State Nursery also prides itself on keeping up with trends in tree species, windbreak designs, and understanding the farmer/landowners needs for trees. There isn't much the State Nursery would do differently. However, they realize that they need to do more to promote or market the program as there isn't much effort in that area. Also, they have noticed that deer, dry spells, and improper site maintenance are the leading causes to unsuccessful tree plantings.

Wyoming:

Wyoming State Forestry Division. 11 May 2009 <http://slf-web.state.wy.us/forestry/snow.aspx>

Contact: Wyoming State Forestry Division, State Forester

John Crisp

1100 West 22nd Street Cheyenne, WY 82002

307-777-6680

forestry@state.wy.us,

Summary: The Wyoming State Forestry Division website gives information about advantages and disadvantages of LSF on its website. The website also provides the requirements for proposal of state funded living snow fences. The Wyoming State Forestry Division partners with the Wyoming Department of Transportation in designing and installing living snow fences. Organizations in Wyoming that have used state funding to build LSF include: Popo Agie Conservation District (<http://www.popoagie.org/fence/index.php>) and Larimer County Conservation District (http://www.lccdnet.org/trees/living_snow_fence.html).

Telephone Interview: The living snow fence program in Wyoming has been fully operational for about ten years; and there were several years prior in which the program developed.

Currently, the program has a \$100,000 per year budget. Seven LSF were planted last year. The program works with the Wyoming Department of Transportation and local conservation districts to fully fund and plant LSF along public roadways. Local conservation districts do the planting and maintenance and are reimbursed for expenses through the program. Conservation districts also work with private landowners when LSF are needed on private land. The program also maintains the LSF for three years and then the maintenance responsibility is on the landowner.

Funding from the Wyoming Department of Transportation has made the program successful and the program would not in operation without that funding. Also, the relationships among the DOT and the local conservation districts have made the program work and be successful. At this point there isn't anything the program would do differently; it is a very successful program.

Canada

Alberta, British Colombia, Manitoba, & Saskatchewan:

"Prairie Shelterbelt Program." AAFC-PFRA Agroforestry Division. 2009. 18 May 2009

<http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1180103439791&lang=eng>

Contact: AAFC-PFRA Shelterbelt Centre Laura Poppy

PO Box 940

Indian Head SK SOG 2K0

agroforestry@agr.gc.ca 306-695-2284

Summary: This program “provides technical services and tree and shrub seedlings for establishment of shelterbelts and other agroforestry, conservation and reclamation projects on agricultural and eligible lands in Manitoba, Saskatchewan, Alberta, ... and British Columbia.”

Telephone Interview: The Prairie Shelterbelt Program is a part of the Agriculture and Agri-Food Canada – Prairie Farm Rehabilitation Administration and has been in operation since 1901. The program operates from Saskatchewan, but also serves Manitoba, Alberta, and British Columbia. It started to encourage settlers to come to the area and to reduce soil erosion. It is a federal program that distributes prairie hardy trees and shrubs primarily to farmers for use in planting shelterbelts. To date the program has distributed over 600 million seedlings to over 700,000 farm clients. The seedlings are grown in the nursery in Saskatchewan, and there are between four to five million trees distributed every year to about 7,000 farmers. Farmers must apply to the program and have at least five acres of land for the trees. The program provides the trees, but leaves planting and maintenance to the landowners. The center provides information on planning and planting the shelterbelts. The shelterbelts are primarily used to reduce soil erosion, although they are also used in snow control. The program provides twenty-eight different plants, both native and imported. The program has a research center that researches tree breeding, value of trees, shelterbelt impact on landscape, energy conservation, biomass, and snow effects. The fact that 600 million trees have been distributed is impressive. Scientists in the research center have made many gains in improving the trees that are used in shelterbelts and their efforts in researching other aspects of the trees and the landscape have contributed greatly to the success of the program. There are many general benefits of shelterbelts (snow control, reduced soil erosion, etc.) that people have come to understand and they appreciate the presence of shelterbelts. The program has seen that putting numbers to things such as amount of money saved, the number of shelterbelts planted, etc. has added to the apparent success. Also, the shelterbelts have changed landscape of the prairie provinces into something more pleasing to the eye. There isn't much the program would do differently, as it is so successful. However, it realizes that there is a need for continual research especially since the needs from 100 years ago have changed. The program has evolved and could evolve more. Right now, the researchers are working to make shelterbelts match the needs of farms and new farming methods. Farmers don't see the value of having shelterbelts as much anymore because there isn't as much soil erosion; therefore, trees could be planted more on periphery of farms rather than in the field. There is also the problem of the trees being maintained and getting them to survive; the program is working to help farmers address this problem.

Ontario – Region of Peel:

“Winter Roads Maintenance.” Region of Peel Public Works. 18 May 2009

<http://www.peelregion.ca/pw/roads/winter-maint/faq-corn-fences.htm>

“Designing and Caring for Windbreaks.” Extension Notes. LandOwner Resource Centre and University of Toronto's Faculty of Forestry, 1995. 18 May 2009

http://www.lrconline.com/Extension_Notes_English/pdf/wndbrk.pdf

Contact: Richard Sparham

905-791-7800, ext. 7825

Summary: The Region of Peel in Ontario has a seemingly active living snow fence program. The University of Toronto published a useful newsletter on windbreaks and the kinds of plants that work well for windbreaks and snow fences in Ontario.

Living Snow Fences

Species Matrix for New York State



State University of New York
College of Environmental Science and Forestry



Justin P. Heavey
Timothy A. Volk

Forest & Natural Resource Management
SUNY ESF

Syracuse, NY
2012

Living Snow Fences Species Matrix

Species selection is an important step in the design of effective and efficient living snow fences. A species matrix assists in the plant selection process for living snow fences by providing a palette of suitable species, and a summary of relevant plant traits to compare and contrast species. Recent research at SUNY ESF has built on previous research (Tabler, 2003) and identified key plant traits for living snow fences. Twenty-eight species that possess the traits relevant to living snow fences have been identified and included in this plant matrix. These species are tolerant to a variety of roadside conditions across New York State, and possess the traits necessary to achieve adequate snow trapping and snow storage capabilities. Every plant species is unique, and this matrix is therefore intended as a selection tool to compare and contrast a variety of plants for living snow fences within the context of design goals and site conditions.

Plant Traits for Living Snow Fences

The morphological traits of height and stem density are the two most important factors influencing the function of living snow fences. Mature height should be at least eight feet to achieve adequate snow storage capacity. Stem density should be 40-60% to achieve optimal snow trapping efficiency and drift shape. Deciduous shrubs and evergreen trees are most suitable for expressing these traits in the landscape. Most species in this matrix have been proven suitable for living snow fences or windbreaks, but some species remain untested, as indicated on the first page of the matrix. Additional physiological traits and ecological tolerances relevant to living snow have also been included in this matrix to assist in plant selection. For example, plants with rapid growth rates are desirable to achieve functional heights and densities as quickly as possible. The traits considered most critical to living snow fences are listed on the following pages for each of the twenty-eight species included in this matrix.

Choosing a Species

A variety of factors should be considered when choosing a species from this matrix for a living snow fence. A thorough analysis of the site conditions should inform the species selection. Tolerances to soil conditions and the potential stressors listed in this matrix can greatly impact the vigor and survival of the fence. Choosing a species that is well suited to the environmental conditions of the site can greatly influence the success or failure of the fence. Considerations such as native status, edible fruit



Shrub-willow living snow fence in late summer. Rt. 30, Grand Gorge, Delaware County, NY.

production, and ornamental flowers can also be considered in the selection process.

Shrub-Willow Living Snow Fences

The shrub-willow cultivars included in this matrix possess many of the desirable characteristics for living snow fences such as sufficient height, density, and rapid growth rate. Shrub-willow living snow fences can be propagated from dormant stem cuttings with greater ease, and lower costs than using rooted stock of other species. Shrub-willows also tolerate a variety of site conditions, and are resistant to most pests and pathogens. Shrub-willows have also been more widely tested as living snow fences in New York State than other species and have been proven effective. Research on shrub-willow living snow fences is ongoing. Additional information on shrub-willows is available at: www.esf.edu/willow

	<u>Common Name</u>	<u>Scientific Name</u>	<u>Family</u>	<u>Native Status</u>	<u>Tested as LSF or windbreak</u>	<u>Growth Form</u>	<u>Planting Stock</u>
Deciduous	common serviceberry	<i>Amelanchier arborea</i>	Rosaceae	Native	No	Multi-stem shrub	Bareroot/container
	caragana	<i>Caragana arborescens</i>	Fabaceae	Introduced	Yes	Multi-stem shrub	Bareroot/container
	silky dogwood	<i>Cornus amomum</i>	Cornaceae	Native	Yes	Multi-stem shrub	Bareroot/container
	redosier dogwood	<i>Cornus sericea ssp. sericea</i>	Cornaceae	Native	Yes	Multi-stem shrub	Bareroot/container
	American hazelnut	<i>Corylus americana</i>	Betulaceae	Native	No	Multi-stem shrub	Bareroot/container
	beaked hazelnut	<i>Corylus cornuta</i>	Betulaceae	Native	No	Multi-stem shrub	Bareroot/container
	Amur privet	<i>Ligustrum amurense</i>	Oleaceae	Introduced	Yes	Multi-stem shrub	Bareroot/container
	northern bayberry	<i>Morella pensylvanica</i>	Myricaceae	Native	Yes	Multi-stem shrub	Bareroot/container
	American plum	<i>Prunus americana</i>	Rosaceae	Native	Yes	Multi-stem shrub	Bareroot/container
	nanking chery	<i>Prunus tomentosa</i>	Rosaceae	Introduced	Yes	Multi-stem shrub	Bareroot/container
	smooth sumac	<i>Rhus glabra</i>	Anacardiaceae	Native	No	Multi-stem shrub	Bareroot/container
	shrub willow var. 'S365'	<i>Salix caprea</i>	Salicaceae	Cultivar	Yes	Multi-stem shrub	Unrooted stem cutting
	shrub willow var 'S25'	<i>Salix eriocephala</i>	Salicaceae	Native	Yes	Multi-stem shrub	Unrooted stem cutting
	shrub willow var. 'SX64'	<i>Salix miyabeana</i>	Salicaceae	Cultivar	Yes	Multi-stem shrub	Unrooted stem cutting
	shrub willow 'fish creek'	<i>Salix purpurea</i>	Salicaceae	Cultivar	Yes	Multi-stem shrub	Unrooted stem cutting
	shrub willow var. 'SX61'	<i>Salix sachalinensis</i>	Salicaceae	Cultivar	Yes	Multi-stem shrub	Unrooted stem cutting
	silver buffaloberry	<i>Shepherdia argentea</i>	Elaeagnaceae	Native	Yes	Multi-stem shrub	Bareroot/container
	common lilac	<i>Syringa vulgaris</i>	Oleaceae	Introduced	Yes	Multi-stem shrub	Bareroot/container
	highbush blueberry	<i>Vaccinium corymbosum</i>	Ericaceae	Native	No	Multi-stem shrub	Bareroot/container
nannyberry	<i>Viburnum lentago</i>	Caprifoliaceae	Native	Yes	Multi-stem shrub	Bareroot/container	
blackhaw	<i>Viburnum prunifolium</i>	Caprifoliaceae	Native	No	Multi-stem shrub	Bareroot/container	
Evergreen	common juniper	<i>Juniperus communis</i>	Cupressaceae	Native	No	Single stem shrub	Bareroot/container
	eastern redcedar	<i>Juniperus virginiana</i>	Cupressaceae	Native	Yes	Single stem tree	Bareroot/container
	Norway spruce	<i>Picea abies</i>	Pinaceae	Introduced	Yes	Single stem tree	Bareroot/container
	white spruce	<i>Picea glauca</i>	Pinaceae	Native	Yes	Single stem tree	Bareroot/container
	blue spruce	<i>Picea pungens</i>	Pinaceae	Native	Yes	Single stem tree	Bareroot/container
	English yew	<i>Taxus baccata</i>	Taxaceae	Introduced	No	Single stem shrub	Bareroot/container
	arborvitae	<i>Thuja occidentalis</i>	Cupressaceae	Native	Yes	Single stem tree	Bareroot/container

	<u>Common Name</u>	<u>Growth Rate</u>	<u>Height base age (ft)</u>	<u>Mature Height (ft)</u>	<u>Lifespan</u>	<u>Temp Min (°F)</u>	<u>Density per Acre (Min)</u>	<u>Density per Acre (Max)</u>	<u>Hedge Tolerance</u>
Deciduous	common serviceberry	Slow	25	36	Moderate	-47	700	1700	Low
	caragana	Rapid	12	12	Moderate	-38	1212	2728	Medium
	silky dogwood	Moderate	7	10	Moderate	-38	1200	4800	Medium
	redosier dogwood	Moderate	12	12	Moderate	-38	1212	4850	Low
	American hazelnut	Moderate	10	10	Short	-33	700	1700	Low
	beaked hazelnut	Moderate	15	15	Long	-47	700	1700	Medium
	Amur privet	Moderate	12	12	Moderate	-38	680	2722	High
	northern bayberry	Slow	9	12	Long	-28	1210	2722	Low
	American plum	Moderate	24	24	Long	-38	700	1200	Low
	nanking cherry	Moderate	8	8	Long	-38	680	1200	Medium
	smooth sumac	Moderate	12	12	Short	-33	300	1200	Low
	shrub willow var. 'S365'	Very Rapid	15	20	Medium	-40	1 per foot	1 per foot	High
	shrub willow var 'S25'	Very Rapid	20	25	Medium	-40	1 per foot	1 per foot	High
	shrub willow var. 'SX64'	Very Rapid	20	30	Medium	-40	1 per foot	1 per foot	High
	shrub willow 'fish creek'	Very Rapid	20	25	Medium	-40	1 per foot	1 per foot	High
	shrub willow var. 'SX61'	Very Rapid	15	25	Medium	-40	1 per foot	1 per foot	High
	silver buffaloberry	Rapid	18	18	Moderate	-38	300	1800	Medium
	common lilac	Moderate	20	20	Moderate	-38	700	1200	High
	highbush blueberry	Moderate	12	12	Moderate	-33	1200	1700	Low
	nannyberry	Slow	28	28	Long	-33	300	1200	None
blackhaw	Slow	16	16	Long	-33	700	1200	Low	
Evergreen	common juniper	Slow	5	10	Long	-43	700	2200	Medium
	eastern redcedar	Slow	25	50	Moderate	-43	300	1200	Medium
	Norway spruce	Slow	35	130	Moderate	-39	300	700	High
	white spruce	Slow	30	100	Moderate	-65	300	700	Low
	blue spruce	Slow	20	100	Long	-38	300	700	Low
	English yew	Slow	25	40	Moderate	-28	300	1200	High
	arborvitae	Slow	25	50	Long	-33	300	1200	High

	<u>Common Name</u>	<u>Moisture Use</u>	<u>Root Depth Minimum (in)</u>	<u>Fertility Requirement</u>	<u>Adapted to Coarse Soils</u>	<u>Adapted to Medium Soils</u>	<u>Adapted to Fine Soils</u>	<u>pH (Min)</u>	<u>pH (Max)</u>	<u>Nitrogen Fixation</u>
Deciduous	common serviceberry	Medium	20	Medium	Yes	Yes	No	4.8	7.5	None
	caragana	medium	16	Low	Yes	Yes	Yes	5	8.5	Medium
	silky dogwood	High	16	Medium	Yes	Yes	Yes	5	7	None
	redosier dogwood	High	20	Low	Yes	Yes	Yes	4.8	7.5	None
	American hazelnut	Medium	20	Medium	No	Yes	Yes	5	7	None
	beaked hazelnut	Medium	16	Medium	No	Yes	No	4.8	7.5	None
	Amur privet	Medium	20	Medium	No	Yes	Yes	5.8	7.5	None
	northern bayberry	Medium	20	Low	Yes	Yes	No	5.5	7.8	Medium
	American plum	Medium	24	Medium	Yes	Yes	No	5	7	None
	nanking cherry	Medium	20	Medium	Yes	Yes	No	5.7	7.2	None
	smooth sumac	Low	24	Low	Yes	Yes	No	5.3	7.5	None
	shrub willow var. 'S365'	Medium	18	Medium	Yes	Yes	No	5.5	8	None
	shrub willow var 'S25'	Medium	18	Medium	Yes	Yes	No	5.5	8	None
	shrub willow var. 'SX64'	Medium	18	Medium	Yes	Yes	No	5.5	8	None
	shrub willow 'fish creek'	Medium	18	Medium	Yes	Yes	No	5.5	8	None
	shrub willow var. 'SX61'	Medium	18	Medium	Yes	Yes	No	5.5	8	None
	silver buffaloberry	Medium	24	Low	Yes	Yes	No	5.3	8	Medium
	common lilac	Medium	14	Medium	Yes	Yes	Yes	5.8	7.8	None
	highbush blueberry	Medium	16	Medium	Yes	Yes	Yes	4.7	7.5	None
	nannyberry	Medium	14	Medium	No	Yes	Yes	5	7	None
blackhaw	Medium	18	Low	No	Yes	Yes	4.8	7.5	None	
Evergreen	common juniper	Low	14	Low	Yes	Yes	Yes	5.5	8	None
	eastern redcedar	Low	20	Low	Yes	Yes	Yes	4.7	8	None
	Norway spruce	Medium	28	Medium	No	Yes	Yes	5	7	None
	white spruce	Medium	30	High	Yes	Yes	Yes	4	8.2	None
	blue spruce	Medium	18	Medium	Yes	Yes	No	5.5	7.8	None
	English yew	Medium	16	Medium	No	Yes	No	5.3	7.8	None
	arborvitae	Medium	30	Medium	Yes	Yes	Yes	5.2	7	None

	<u>Common Name</u>	<u>Anaerobic Tolerance</u>	<u>Drought Tolerance</u>	<u>Salinity Tolerance</u>	<u>Coppice Potential</u>	<u>Deer Browse</u>	<u>Seed Spread Rate</u>	<u>Vegetative Spread Rate</u>	<u>Edible Fruit/Nut</u>	<u>Ornamental Flower</u>
Deciduous	common serviceberry	Medium	Low	Low	No	Low	Moderate	None	Yes	Yes
	caragana	Low	High	Medium	Yes	Low	Moderate	None	No	Yes
	silky dogwood	Medium	Low	None	Yes	Low	Slow	Slow	No	Yes
	redosier dogwood	High	Low	None	No	High	Slow	Moderate	No	Yes
	American hazelnut	None	Medium	None	No	Medium	Slow	None	Yes	No
	beaked hazelnut	None	Medium	None	No	Medium	Slow	Slow	Yes	No
	Amur privet	Low	Medium	None	Yes	Low	Slow	None	No	Yes
	northern bayberry	Low	High	Medium	No	Low	Slow	Slow	No	No
	American plum	Medium	None	Low	No	Medium	Slow	None	Yes	Yes
	nanking cherry	None	Medium	Low	Yes	Low	Slow	None	Yes	Yes
	smooth sumac	Low	Medium	Medium	Yes	Low	Slow	Moderate	No	No
	shrub willow var. 'S365'	Medium	Medium	Medium	Yes	Medium	None	None	No	No
	shrub willow var 'S25'	Medium	Medium	Medium	Yes	Medium	None	None	No	No
	shrub willow var. 'SX64'	Medium	Medium	Medium	Yes	Medium	None	None	No	No
	shrub willow 'fish creek'	None	Medium	Medium	Yes	Medium	None	None	No	Yes
	shrub willow var. 'SX61'	Medium	Medium	Medium	Yes	Medium	None	None	No	No
	silver buffaloberry	None	Medium	High	Yes	Medium	Slow	Rapid	No	Yes
	common lilac	None	Medium	Medium	No	Low	Slow	Moderate	No	Yes
	highbush blueberry	Medium	Low	High	No	Medium	Slow	None	Yes	No
nannyberry	Medium	Low	None	No	Low	Slow	None	No	Yes	
blackhaw	None	Medium	None	Yes	Medium	Slow	None	Yes	Yes	
Evergreen	common juniper	None	High	Medium	No	Low	Slow	None	No	No
	eastern redcedar	Low	High	Low	No	Low	Rapid	None	No	No
	Norway spruce	None	Medium	Low	No	Low	Slow	None	No	No
	white spruce	None	High	Medium	No	Low	Slow	Slow	No	No
	blue spruce	None	Medium	Low	No	Low	Moderate	None	No	No
	English yew	None	Medium	Medium	No	Low	None	None	No	No
	arborvitae	Medium	Low	Medium	No	High	Moderate	None	No	No

Glossary of Terms

(Adapted from USDA Plant Database: <http://plants.usda.gov/charinfo.html>)

Native Status

Native status of the species. "*Native*" rating indicates the species is native to the northeast or North America. "*Introduced*" rating indicates the species is not native to the continental US and is also not listed on any state or federal invasive species list according to the USDA Plant Database as of June, 2012. "*Cultivar*" rating indicates a cultivated variety obtained through traditional breeding of native and/or non-native species.

Tested as LSF or Windbreak

Presence of information in the literature or on the web that indicates the species has been successfully used as a living snow fence or windbreak planting.

Growth Form

General morphology of species in terms of tree or shrub, and single or multiple main stems.

Planting Stock

Type of planting stock commonly used and commercially available.

Growth Rate

Rate of growth after successful establishment relative to other species with same growth form.

Height at Base Age

Maximum height under ideal conditions, at a base age. The base age is 10 years for shrubs and 20 years for trees.

Height at Maturity

Expected height of species at maturity. This is an estimate of the median mature height of a species or cultivar. Within a species mature height varies so this estimate is provided only to give a rough idea for planning purposes.

Lifespan

Expected lifespan relative to other species with the same growth form. For trees: Short < 100; Moderate 100 - 250; Long >250. Life spans for shrubs are not quantified.

Temp Min

Cold hardiness rating of the species, or the lowest winter temperature the plant will tolerate.

Density per Acre Min/Max

Recommended minimum/maximum number of plants per acre.

Hedge Tolerance

Tolerance of species to hedging (close cropping).

Moisture Use

Ability to use (i.e., remove) available soil moisture relative to other species in the same (or similar) soil moisture availability region.

Root Depth Minimum

The minimum depth of soil required for good growth.

Fertility Requirement

Relative level of nutrition (N, P, K) required for normal growth and development.

Adapted to Coarse/Medium/Fine Soils

Indicates species ability to establish and grow in soil with a coarse/medium/fine textured surface layer.

Coarse Textured soils include: sand, coarse sand, fine sand, loamy coarse sand, loamy fine sand, loamy very fine sand, very fine sand, and loamy sand.

Glossary of Terms

(continued)

Medium Textured soils include: silt, sandy clay loam, very fine sandy loam, silty clay loam, loam, fine sandy loam, sandy loam, coarse sandy loam, and clay loam.

Fine Textured soils include: Sandy clay, silty clay, and clay.

pH Min/Max

The minimum/maximum soil pH of the top 12 inches of soil within the species known geographical range.

Nitrogen Fixation

Amount of atmospheric nitrogen fixed by the species in a monoculture. Rating of "None" is 0 lb. N/acre/year; "Low" <85; "Medium" 85-160; "High" >160.

Anaerobic Tolerance

Relative tolerance to anaerobic (saturated) soil conditions.

Drought Tolerance

Relative tolerance of the species to drought conditions compared to other species with the same growth form from the same geographical region.

Salinity Tolerance

Species tolerance to soil salinity. Tolerance to a soil salinity level is defined as only a slight reduction (not greater than 10%) in plant growth. None = tolerant to a soil with an electrical conductivity of the soil solution extract of 0-2 dS/m; Low = tolerant to 2.1-4.0 dS/m; Medium = tolerant to 4.1-8.0 dS/m; High = tolerant to greater than 8.0 dS/m

Coppice Potential

Ability of a species to respond favorably to coppicing. Coppicing completely removes the canopy of woody plants, cutting them just above ground level.

A favorable response to coppicing for LSF applications is defined as increased number of stems, increased vigor, and/or higher optical density during the snow season.

Deer Browse

Palatability of species to deer and other browsers relative to other species with similar growth form.

Seed Spread Rate

Capability of the species to spread through its seed production compared to other species with the same growth form.

Vegetative Spread Rate

Capability of the species to spread vegetatively (suckering, rhizomes, layering, etc) compared with other species with the same growth form.

Edible Fruit/Nut

Species is capable of producing fruit or nut product palatable to humans as an auxiliary benefit.

Ornamental Flower

Species produces flowers that are conspicuous from landscaping aesthetics standpoint.

Living Snow Fences Species Matrix for New York State

Justin P. Heavey
Timothy A. Volk

Forest & Natural Resource Management
SUNY ESF

Syracuse, NY
2012

Matrix data adapted from:

USDA Plant Database: www.plants.usda.gov
and

SUNY ESF Willow Facts Sheets: www.esf.edu/willow

Works Cited:

Tabler, R.D. 2003. *Controlling blowing and drifting snow with snow fences and road design*.
Tabler and Associates. Niwot, CO.

Prepared by SUNY ESF for New York State Department of Transportation

Photos courtesy of SUNY ESF & NYSDOT



Shrub-willow living snow fence on I-81 SB in Preble, Cortland County, NY



Spruce living snow fence on Rt. 167, Manheim, Herkimer County, NY.

Task 1-B: Guidelines for Living Snow Fences

Task 1-B: Guidelines for Living Snow Fences

Overview:

Based on the literature review conducted in Task 1-A, the next project task was to prepare a series of fact sheets that covers practical issues related to the design and implementation of living snow fences, and related theoretical aspects of snow movement, categorized into the following fact sheet topics.

1. Introduction to Living Snow Fences
2. Site Assessment
3. Design
4. Species Selection
5. Site Preparation
6. Planting Techniques
7. Maintenance

Fact Sheet 1 of 7
Introduction to Living Snow Fences
(1 page)

Living Snow Fences

Fact Sheet Series - Fact Sheet #1

Introduction to Living Snow Fences



State University of New York
College of Environmental Science and Forestry

Living Snow Fences

Blowing and drifting snow on roadways can increase the cost of snow and ice control, increase travel time and reduce visibility and driver safety. Living snow fences are strips of densely planted vegetation designed to control blowing and drifting snow on roadways. Living snow fences disrupt wind patterns, causing snow to be deposited in drifts on both the upwind and downwind side of the fence before it reaches the roadway. This fact sheet series offers a basic guide to planning, installing, and maintaining a living snow fence. This fact sheet series includes an introduction and six additional fact sheets on topics that encompass the life cycle of a living snow fence: *Site Assessment, Design, Species Selection, Site Preparation, Planting, and Maintenance*.

This fact sheet series is an introductory guide to living snow fences. Designers should consult other resources listed at the end of each fact sheet for more detailed information on the structure and function of living snow fences. Living snow fences take several years to become effective, but can provide decades of blowing snow control if properly designed, installed and maintained.

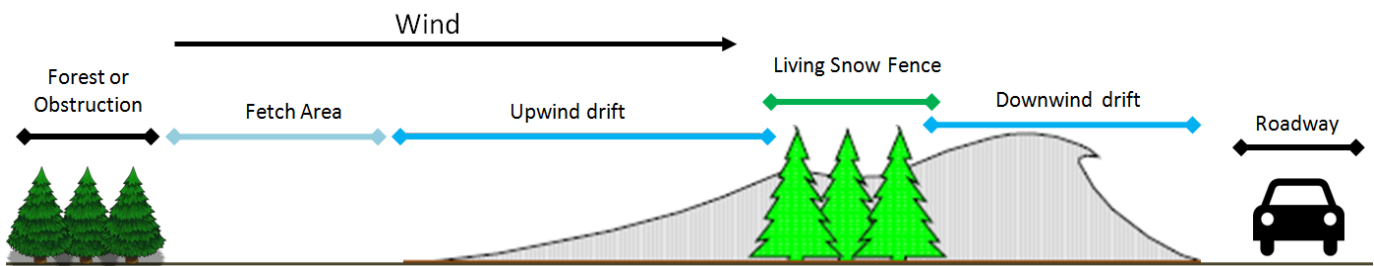


Figure 1 - Adapted from Tabler (2003)

Figure 1 above (adapted from Tabler, 2003) illustrates the basic function of a living snow fence from a cross-sectional viewpoint. Snow is picked up by the wind in the “Fetch” area and transported toward the roadway. The fetch is the unobstructed area upwind of the snow fence. The living snow fence disrupts wind patterns creating turbulence around the fence, causing snow to be deposited in drifts on the upwind and downwind side of the fence, before it reaches the roadway. More detailed information for living snow fence design is referenced below. The full fact sheet series is available online at the web address at the bottom of the page.

Additional Resources

Gullickson, D., Josiah, S.J., Flynn, P., 1999. *Catching snow with living snow fences*. University of Minnesota.

Tabler, R.D. 2003. *Controlling blowing and drifting snow with snow fences and road design*. Tabler and Associates. Niwot, CO.

J.P. Heavey & T.A. Volk
SUNY ESF, 2013

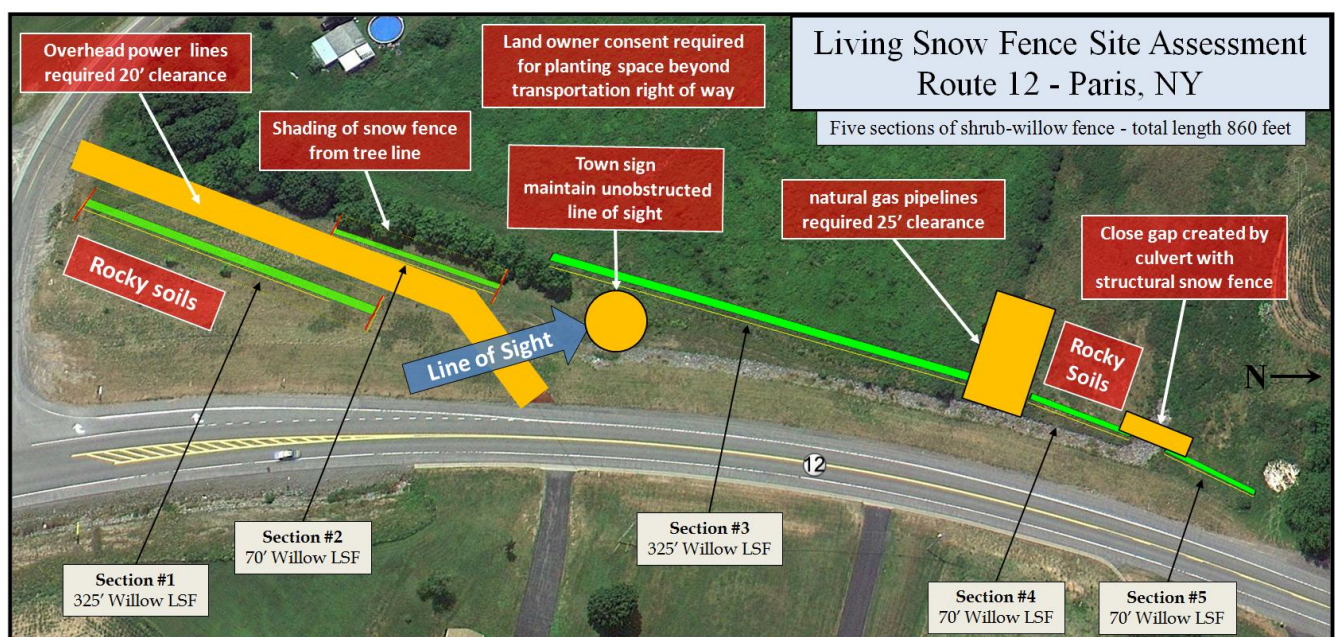
Fact Sheet 2 of 7
Site Assessment
(3 pages)



Site Assessment

Site assessment is an important step in the establishment and long-term success of living snow fences. Once an area has been selected for a living snow fence installation, site assessment informs the design and planting phases. Multiple site visits may be necessary throughout the design process. The following checklist offers a general methodology for living snow fence site assessment that can be modified as needed by the design team based on the specifics of the site and design goals.

- ◆ Identify the problem by determining the source of blowing snow and the potential solutions using living snow fences. Refer to Tabler (2003) chapter 4 for more specific information on blowing snow problem identification.
- ◆ Collect accounts of winter road conditions and drifting patterns. In collecting accounts, ensure that information is gathered from workers who plow or maintain a given highway segment. Such people are often the most familiar with the snow problem at a site. If possible, the design team should observe winter road and drifting conditions firsthand.
- ◆ Make at least one site visit in the company of as many stakeholders as possible (DOT staff, contractors, landowners, etc). Discuss any site-specific challenges and opportunities while in the field with all stakeholders.
- ◆ Examine aerial photos and use mapping software to measure site characteristics, such as fetch distance, and to visualize potential designs and site challenges. An example is depicted below. The proposed sections of living snow fences are shown in green, and site challenges identified in the site assessment phase are identified by the red caption boxes.



Living Snow Fences

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Living Snow Fence Site Assessment



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- ◆ Identify any permit requirements or regulatory agency concerns. For example, determine if the site is in an environmentally sensitive watershed where fertilizer or herbicide use is restricted, or near utility right of ways that must be kept clear of woody vegetation.
- ◆ Consider the existing vegetation on site, topography, fences, buildings, open spaces, and any other factors that would affect wind patterns or plant growth. Refer to Tabler (2003) chapter 4 for more specific information about landscape features than can be detrimental or beneficial to living snow fence function.



Site assessment for a living snow fence installation in Hamburg, NY in 2009

Soil Assessment

Soil quality is a critical factor in the survival and vigor of living snow fences. Soils should be thoroughly evaluated in the site assessment phase to determine if the quality of the soil is sufficient to support a living snow fence and optimal growth rates. If soils are determined to be of poor quality, a living snow fence installation may not be possible, or significant efforts to improve the soil may be required. The critical factors in assessing soil quality are: soil depth, drainage, fertility, percentage of rocks by volume, and soil texture.

- ◆ Begin the soil assessment by observing the existing vegetation on the site. This will give a rough indication of soil conditions. If the site supports lush woody vegetation or agricultural crops, the soil quality is likely sufficient for a living snow fence. If existing vegetation is sparse or primarily herbaceous (non-woody), this may be an indication of poor or degraded soils. Soils in or near the right of way may be degraded from previous construction activities. Note the presence of wetland indicator species, such as sensitive fern or cattails on the site, as this may indicate saturated soils and the presence of wetlands that may hinder living snow fence growth and require special permits.
- ◆ Consult the Natural Resource Conservation Service (NRCS) soil survey maps (websoilsurvey.nrcs.usda.gov) for site-specific information on soil depth, drainage class, fertility, and texture. Loams and sandy loams are the preferred soil texture of most species. Soils with high clay content may impede drainage. NRCS drainage classification of the soils should be listed as “well

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drained” to “moderately well drained”. “Poorly drained” and “somewhat poorly drained” soils will cause stunted growth or mortality in most species and will require more precise plant selection or substantial site modifications to improve drainage.

- ◆ Take soil samples and have the soil tested by a university lab or environmental engineering firm for: pH, percentage of organic matter, soluble salts, available nitrogen, phosphorus, potassium, calcium, and magnesium. Follow the soil sampling procedures specified by the lab that will do the analysis. For woody plants, sampling the top 6 inches to 10 inches of soil is the most critical. Evaluate the chemical properties of the soil and consider the need for soil amendments in the design, species selection, site preparation, and installation phases.
- ◆ Dig a soil pit on the planting strip at several locations across the installation site to expose the soil profile to a depth of 24 inches. Examine the soil profile in each pit to supplement and confirm NRCS data. Observe and evaluate the soil layers, textures, depths, and the percentage of rocks in each layer.
 - If rocks, debris, or large roots make up more than 50 percent of the soil volume, the site is likely unsuitable for a snow fence installation.
 - Determine the depth to root restricting layer (bedrock, clay, water table, etc) and make sure there is sufficient depth for proper root development. Depth to restricting layer should be at least 18 inches.
 - Confirm the NRCS soil drainage classification at each soil pit across the site as indicated by the presence of soil mottling. Mottling is indicated by the presence of distinctive orange and grey soil particles, both occurring at the same depth in the soil profile. This indicates the depth to a seasonal water table and probable root restricting layer. High quality sites with adequate drainage will show no signs of mottling at depths of 24” or greater. If mottling is observed at depths 12 inches or less, the site may be too wet and unsuitable for planting. Some tree and shrub species will tolerate wet conditions, but only a limited number species suitable for living snow fences will thrive and grow rapidly in saturated soils.
- ◆ Consult your local environmental specialist, extension agent, or NRCS staff if you have questions about any of the steps in the soil assessment process.

Additional Resources

Gullickson, D., Josiah, S.J., Flynn, P., 1999. *Catching snow with living snow fences*. University of Minnesota.

Tabler, R.D. 2003. *Controlling blowing and drifting snow with snow fences and road design*. Tabler and Associates. Niwot, CO.

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Fact Sheet 3 of 7

Design

(13 pages)

Living Snow Fences

Fact Sheet Series - Fact Sheet #3

Living Snow Fence Design



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Living Snow Fence Design

The design of living snow fences involves several components. This fact sheet offers a general protocol for the basic elements of design: Fence Orientation, Snow Fall, Fetch Distance, Snow Transport, Required Height, Selecting a Design Age, Optical Porosity, Fence Capacity, and Setback. The general guidelines presented here are adapted from “Controlling blowing and drifting snow with snow fences and road design” (Tabler, 2003), and “Climatological analysis for snow mitigation in New York State” (Tabler, 2000). It is recommended that these sources be consulted to supplement the basic information provided in this fact sheet. After the site assessment phase has sufficiently identified the blowing/drifting snow problem at a site (see Fact Sheet #2 of this series and Chapter 4 in Tabler 2003), the steps in this fact sheet can be followed in the order in which they are presented to create a basic living snow fence design to address the problem. A case-study example from a real living snow fence designed using this step-by-step protocol is provided at the end of the fact sheet. Models from Tabler (2003) were created in metric units and all equations in this fact sheet require all inputs to be in metric units to obtain valid results.

Step 1: Determine Fence Orientation

Snow fences should be oriented according to the direction of the prevailing winter wind relative to the roadway. The direction of prevailing wind can be highly localized, and it is recommended that direction be determined based on site-specific observations such as the direction of blowing snow across the road, or the direction of drifts formed around sign posts or other objects on the site. Wind direction can be more precisely quantified using a data logging anemometer. Once wind direction is determined, the orientation of the fence is selected based on the acute angle (α) of the wind direction relative to the roadway. In most cases, the acute angle (α) will be between 55° and 90° (Figure 1), in which case fences should be oriented parallel to the road. In some cases, the acute angle (α) will be less than 55° . In this case fences may need to be oriented perpendicular to the wind (Figure 2).

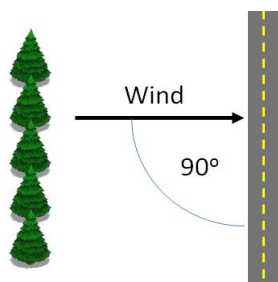


Figure 1 - Acute angle (α) is between 55° and 90° , fence is oriented parallel to the roadway
Diagram by SUNY ESF

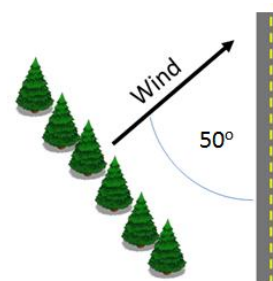


Figure 2 - Acute angle (α) is less than 55° , fence is oriented perpendicular to the wind
Diagram by SUNY ESF

Fences should be designed without any gaps, to provide continuous protection of the roadway. If a continuous fence is not possible due to site obstructions, fences can be designed in multiple sections that are slightly offset and overlapped by approximately 20 feet to prevent blow through between sections. If planting is not possible in certain areas due to obstructions such as a pavement or a drainage ditch,



structural snow fence segments can be used in conjunction with living snow fences to close gaps and prevent blow-through in these areas.

Step 2: Estimate Snowfall Water Equivalent over the Drift Accumulation Season (S_{we})

An estimate of the snowfall water equivalent over the drift accumulation season (S_{we}) is the first of two critical inputs for determining the quantity of blowing snow at a site (step 4). "Water equivalent" refers to the mass of liquid water equivalent of fallen snow, snow having a lower density than water. Note that S_{we} is different than the annual snowfall total for an area, the former being delimited by snow that falls before or after sustained drift growth occurs (Tabler, 2003). S_{we} in New York State can be calculated using the following equation from Tabler (2000):

$$S_{we} = (-695.4 + 0.076 * \text{Elev} + 17.108 * \text{Lat}) (0.0254) (0.10)$$

Where:

S_{we} is the water equivalent of snowfall over the drift accumulation season in meters

Elev is the elevation of the snow fence site in meters

Lat is the degrees north latitude of the snow fence site

Note that (0.10) represents the assumed water equivalent of snowfall. If the water equivalent of snowfall is known to be different at the snow fence site, this value can be adjusted accordingly. This equation applies only to New York State and S_{we} in other regions must be measured or estimated using other methods.

Step 3: Measure Fetch Distance (F)

Measuring the fetch distance provides the second critical input for determining the quantity of blowing snow in step 4. Fetch distance (F) as defined by Tabler (2000) as "... the distance contributing blowing snow to a downwind location. The upwind extent of the fetch is marked by some topographic feature across which there is no appreciable snow transport such as a wooded area... that causes blowing snow to be deposited." (Figure 3). Fetch measurements must taken in (or converted into) metric units of meters and can be measured using mapping software or a field survey.

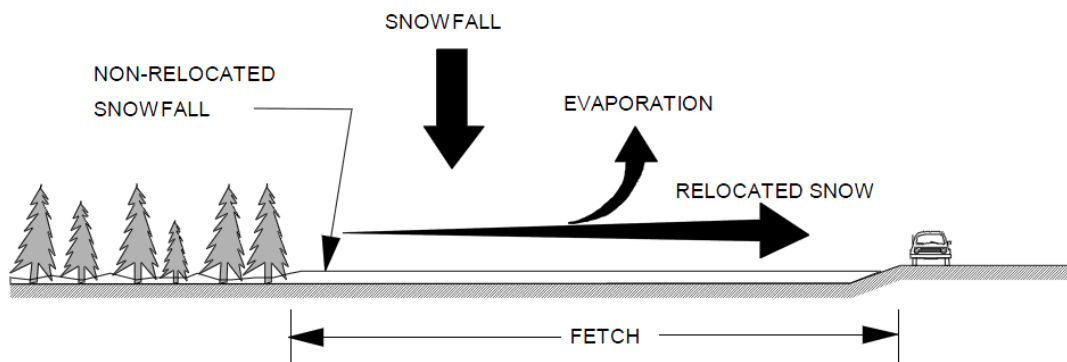


Figure 3 – Fetch distance for design of living snow (Tabler 2000)



Step 4: Calculate Snow Transport (Q)

Snow transport (**Q**) is the quantity of blowing snow at a site over the drift accumulation season. Calculating **Q** provides an estimate of the quantity of blowing snow that will encounter the fence in an average year. **Q** is measured in units of metric tons of snow per linear meter of fence, abbreviated “t/m”. The following equation by Tabler (2000) provides an output for **Q**:

$$Q = (1500)(0.17)(S_{we})(1-0.14^{F/3000})$$

Where:

Q is the average annual quantity of snow transport in units of t/m

(S_{we}) is the water equivalent of snowfall in meters from Step 2

F is the Fetch distance in meters from Step 3, with a maximum value of 3000

Note that (0.17) is the assumed relocation coefficient, or the percentage of fallen snow transported by the wind. This value is a statewide average recommended for snow fence design in New York by Tabler (2000). If a different value is known or measured at a site, it can be used in place of 0.17. The relocation coefficient in other regions outside of New York State may be substantially higher, and a climatic study should be conducted to determine an appropriate value for each region.

Step 5: Calculate Required Height (H_{req})

The required height (**H_{req}**) of the living snow fence in meters, based on the estimate of snow transport (**Q**) from Step 4, is calculated using the follow equation from Tabler (2003):

$$H_{req} = (Q/8.5)^{0.455}$$

Where:

H_{req} is the required minimum height of the snow fence in units of meters

Q is the quantity of snow transport in units of t/m from Step 4

This equation calculates the *minimum* height of the fence that is required to capture the snow transport (**Q**) in an equilibrium (maximum capacity) drift with a downwind drift length of approximately 35 times the required height (35**H_{req}**). Snow transport in any given year may exceed the average (**Q**), which will increase the **H_{req}** output of this formula. The height of living snow fences is not static, and increases over time as plants grow. Based on estimates of statewide **Q** values (Tabler 2003), most tree and shrub species recommended for living snow fences in New York State will exceed **H_{req}** early in their lifecycle (Heavey, 2013).

Refer to Fact Sheet #4 of this series (“*Species Selection*”) for recommended species, mature heights, and growth rates. Selecting a species that will exceed the required height will increase snow storage capacity of the fence, and reduce the length of the downwind drift over time. Note that this equation provides the required height on level ground. Terrain sloping down toward the road will increase the storage capacity



while terrain sloping up toward the road will reduce storage capacity, resulting in a potential decrease or increase in H_{req} , respectively. The influence of topography can be modeled using the "SNOWMAN" (Snow Management) software developed by NYSDOT and the University of Buffalo for Bentley MicroStation CAD.

Step 6: Select a Species and Design Age (a)

Because the variables of height, porosity, capacity, and drift length of living snow fences change over time, selecting a design age (**a**), which corresponds to a value for each of these variables, is a useful step in the design process. The estimated Porosity and Height (Steps 7 and 8) at the chosen design age will depend on the species that is selected for planting. Design age can be selected based on the type and species of vegetation used.

Examples of design ages would be 4 years (**a** = 4) when a fast growing shrub species is expected to begin trapping snow, 8 years when the same fence is expected to double in height from age 4, or 15 years when the fence is expected reach its full mature height. Modeling several different design ages can provide an estimate of how the function of the fence will change over time, and inform the important design decision of setback distance. Selecting one design age to start with in the current step provides a starting point for modeling the function of a living fence over time.

Step 7: Estimate Optical Porosity (P) in the design age

Porosity is the percentage of area not obstructed by vegetation when a fence is viewed at a perpendicular angle during winter. This concept is illustrated in Figure 4, showing a photograph taken at a 90° angle of a shrub-willow living snow fence in winter. The percentage of open space (in red), not blocked by vegetation, is the optical porosity (**P**). In this photo of a 6 year old shrub-willow fence, the Porosity is 57 percent (43 percent density). A living snow fence with 50 percent porosity has the highest amount of snow storage capacity. Living snow fences with porosity above 70 percent are ineffective at trapping snow. Fences with porosity below 50 percent have less snow storage capacity, but cause a higher percentage of snow to be stored on the upwind side of the fence, shortening the length of the downwind drift. A common target range for porosity when designing a living snow fence is between 40 to 60 percent.

As with fence height, porosity of living snow fences is not static. Porosity generally decreases with time as plants grow and fill in the open space. The porosity that a living snow fence will reach and the time frame will depend on the choice of species, plant spacing, and number of rows. Using smaller spacing between plants and multiple offset rows of vegetation will achieve the target porosity range of 40 – 60 percent more quickly. To reach the target porosity of 40 – 60 percent in an acceptable time frame, the following general guidelines for design can be used to select a planting pattern for general vegetation types of species recommended for living snow fences:



Evergreen Trees: 6 to 8 feet spacing between trees, two offset rows, 6 to 8 feet spacing between rows
Shrubs: 3 to 4 feet spacing between plants, two offset rows, 3 to 4 feet spacing between rows
Shrub-willows: 2 feet spacing between plants, two offset rows, 2.5 feet spacing between rows



Figure 4 – Photo of a shrub-willow living snow fence in winter. Plant stems are pictured in the foreground, in front of a red backdrop highlighting the optical porosity (open space) of the fence
Image by SUNY ESF

For evergreen trees and shrubs, the planting pattern also depends on the size of planting stock used. Planting large trees and shrubs will achieve the target porosity more quickly than smaller planting stock or seedlings planted at the same spacing. Use species specific information as much as possible and refer to the other fact sheets in this series (#4 “*Species Selection*”, and #6 “*Planting*”) for more guidelines on recommended species and planting techniques. Visiting living snow fences planted in previous years is also a good way to understand the change in porosity over time.

These guidelines should allow the design team to estimate a target porosity value that is expected at the chosen design age (**a**) from Step 6, or a default value of 0.50 can be used in the next steps of design. It is also important to remember that some vegetation types and planting pattern combinations, such as double rows of evergreen trees, will begin to act as non-porous barriers as they mature, with the result being that the majority of snow is stored on the upwind side of the fence, and the length of downwind drift is reduced (Tabler, 2003). Porosity data collected from numerous living snow fences of various vegetation types and ages is depicted in the scatter plot and regression equation shown in Figure 5, which can also be used to estimate porosity at a chosen design age.

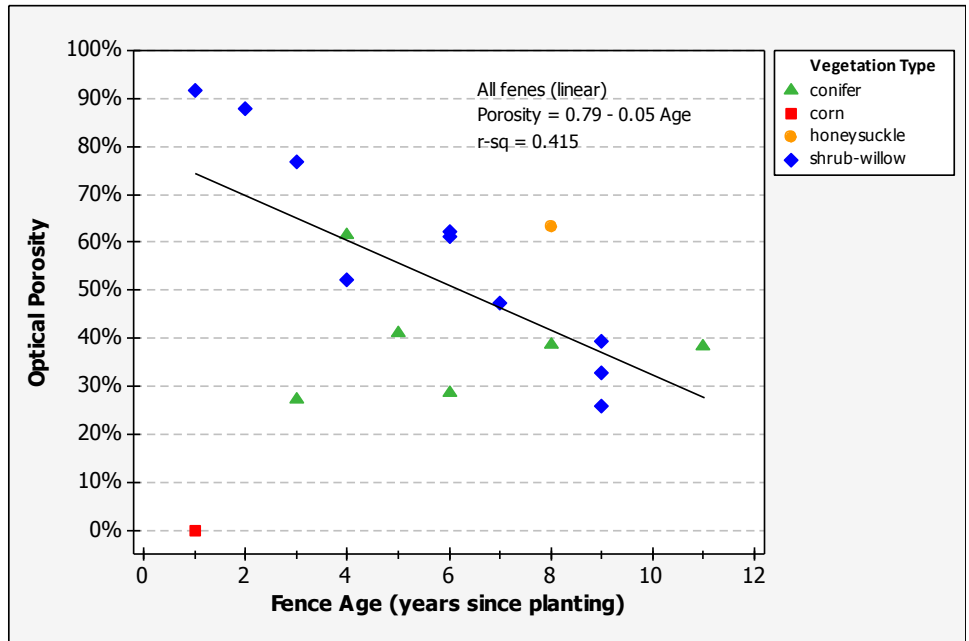


Figure 5 - Fence age versus optical porosity (P) of 18 living snow fences of various species in New York State.
Diagram by Heavey (2013)

Step 8: Estimate Height (H) and Fence Capacity (Q_c) in the design age

It is important to remember that with living snow fences, height increases and porosity decreases over time. As height increases, storage capacity of the fence also increases in a similar trend. As porosity decreases below 50 percent, capacity decreases, but a higher percentage of snow is stored on the fences upwind side. Height at the design age can be estimated based on the chosen species and known growth rates of that species or vegetation type (refer to fact sheet #4 in this series "Species Selection"), or from the scatter plot and regression equation in Figure 6.

Once the estimated height and porosity in the design age have been determined, the snow storage capacity of the fence (Q_c) in the design age can be modeled using the following equation from Tabler (2003):

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

Where:

- Q_c is the snow storage capacity of the fence in units of t/m
- P is the estimated porosity at the design age (a) from Step 7
- H is estimated height at the design age (a) in meters



Storage capacity (Q_c) can then be compared to snow transport (Q) from Step 4 to determine if capacity in the design age is equal to or greater than the average annual snow transport. If capacity is found to be greater than transport, the length of the downwind drift and the required setback will be reduced to some fraction of the maximum $35H_{req}$ as explained in Step 9 below.

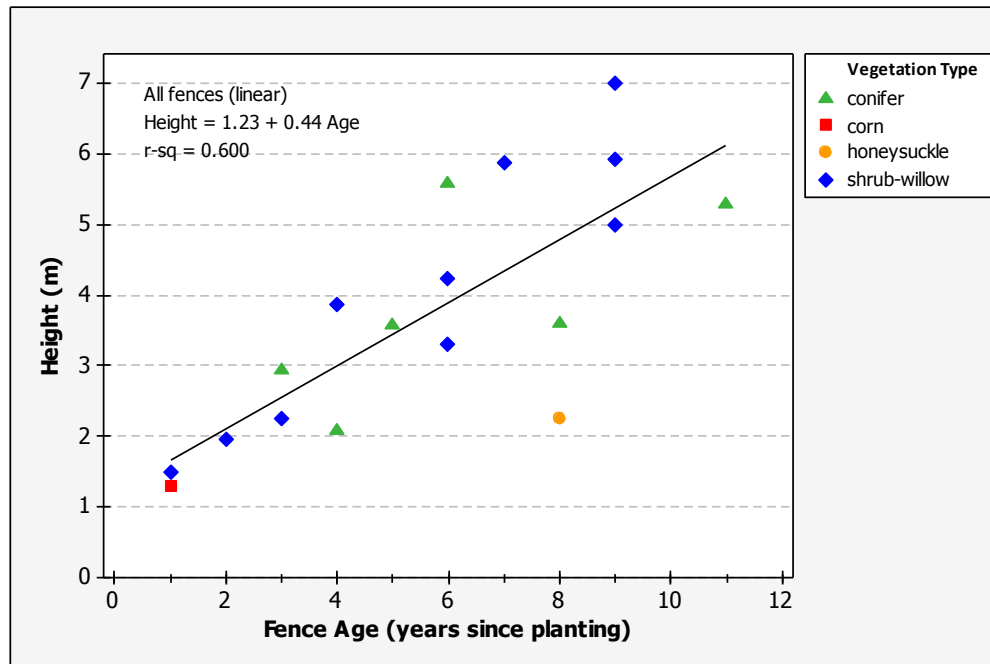


Figure 6 - Fence age versus height (H) of 18 living snow fences of various species in New York State Diagram by Heavey (2013)

Step 9: Calculate Setback Distance

Setback is the distance from the edge of the roadway to the living snow fence. The estimated length of the downwind drift is the primary determinate of appropriate setback distance. Setback must be large enough to accommodate the entire downwind drift, but not excessively large, as this can cause blowing snow problems between the fence and the road, and also inhibit snow fences in areas where right of way planting space is limited. The simplest method for calculating setback for living snow fences (without modeling different design ages) is to use following equation from Tabler (2003):

$$D = (\sin \alpha)(35H_{req})$$

Where :

D is the setback distance in meters

α is the acute angle of the wind to the road from Step 1

H_{req} is the required height of the fence from step 5



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Note that the output for **D** in this equation is based on the minimum required height of the fence (**H_{req}**), not the actual height. **D** is therefore an estimate of the maximum drift length on a fence of the required height, based the snow transport quantity (**Q**). The length of the downwind drift in this case would be approximately 35 times the required height of the fence, or **35H_{req}**, slightly modified by the acute angle of the wind (**α**) in some cases. This represents a conservatively large estimate of the required setback, allowing sufficient space for a full capacity drift of the maximum length to form on a fence of the minimum height. If the species of trees or shrubs that are planted have a mature height that is greater than **H_{req}**, the length of the downwind drift will be reduced to some fraction of **D** as a result of the excess height and storage capacity (see Figure 7 and Figure 8).

A more precise setback distance can be calculated by modeling the length of the downwind drift over time, and deciding the best setback option in the context of site conditions, available right of way planting space, and the long term snow and ice management goals of the site. Downwind drift length and the required setback of living snow fences change over time based on the interplay of height, porosity, and the resulting storage capacity (**Q_c**) relative to snow transport (**Q**). This dynamic is illustrated in Figure 7 and Figure 8, and can be modeled using the following equation from Tabler (2003):

$$L = \{[10.5 + 6.6(A/A_e) + 17.2(A/A_e)^2]/34.3\}(12 + 49P + 7P^2 - 37P^3)(H_{req})$$

Where:

- L** is the length of the downwind drift in meters at design age (**a**) from Step 6
- (A/A_e)** is equivalent to transport/capacity (**Q/Q_c**) from Steps 4 and 8
- P** is porosity at design age (**a**) from Step 6
- (H_{req})** is the required height of the fence from Step 5

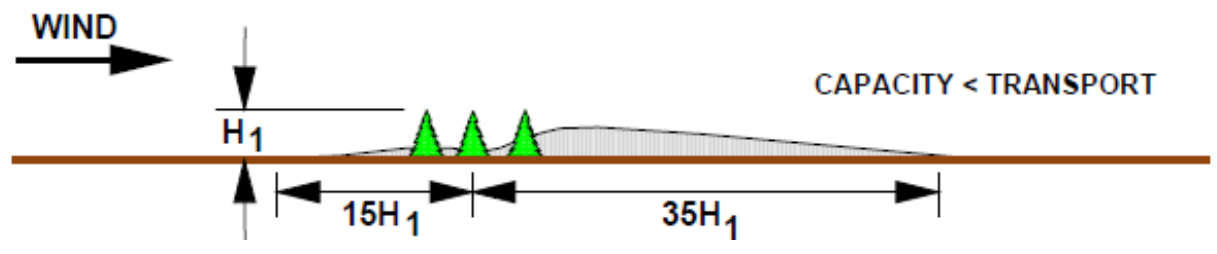


Figure 7 - When fence capacity (**Q_c**) is less than or equal to snow transport (**Q**), the downwind drift length extends to the maximum distance of **35H**, or thirty five times the height of the fence. Diagram from (Tabler, 2003).

Living Snow Fences

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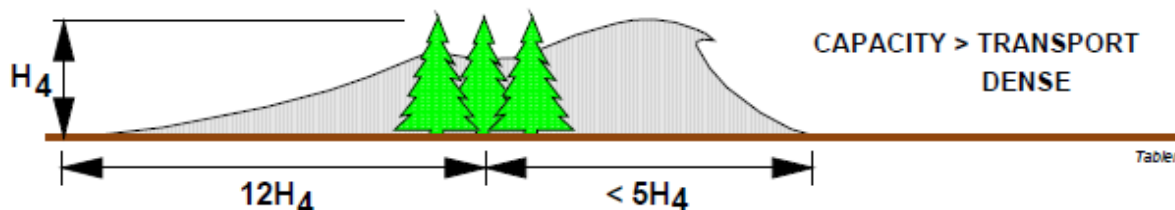


Figure 8 - When fence height (H) is greater than H_{req} , fence capacity (Q_c) becomes greater than snow transport (Q), the downwind drift length (L) is reduced, and the setback distance can be less than $35H$. Diagram from (Tabler, 2003).

Changes in drift shape and length in response to fence height and porosity are based on the aerodynamics of suspended snow particles encountering a porous barrier (i.e. snow fence). Drift formation occurs in distinct stages, illustrated in Figure 9 from Tabler (2003). The maximum drift length occurs in the final stage of drift formation when the fence is at full capacity (equilibrium). If capacity exceeds transport ($Q_c > Q$), living snow fences will not fill to maximum capacity over the drift accumulation season, and the drift will terminate prior to the maximum length of 35 times the height of the fence (Tabler, 2003). The larger the storage capacity relative to transport, the shorter drift length will be. More information on this topic is available in Tabler (2003) and Heavey (2013), referenced at the end of this fact sheet and available for download at www.esf.edu/willow.

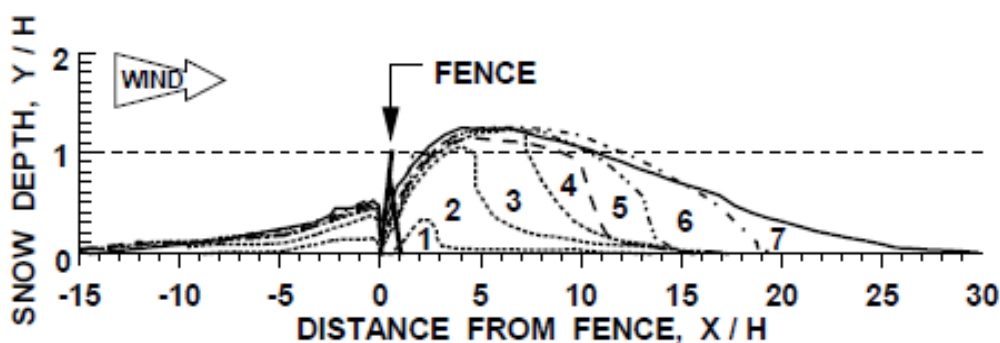


Figure 9 – Stages of drift formation observed around a 50 percent porous structural snow fence (the same principles of drift formation also apply to living snow fences)
Source: Tabler (2003)

It is recommended that drift length be modeled at several different design ages (a) by repeating Steps 6 through 9, and the design team then chose a setback that is most appropriate in the context of estimated fence performance over time, the available right of way space or other planting limitations of the site, and the long term snow and ice management goals for the specific location that the fence is to be installed.



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Available right of way space is often an important consideration when selecting a setback distance, as many locations across the state with blowing snow problems have limited right of way space available for planting, and acquiring additional land may not be feasible. Estimating drift length at different design ages can inform the design team whether or not a living snow fence is feasible on sites with limited right of way space. A temporary structural snow fence can also be used in conjunction with a living snow fence and reduced setback, to prevent snow encroaching on the road while the living fence grows to a height in which the downwind drift length is reduced.

Living Snow Fence Design Example

The following design example uses the steps outlined in this fact sheet, applied to a case-study of a real shrub-willow living snow fence that was installed through the cooperative efforts of SUNY ESF and NYSDOT. The variables used in this example represent the real values collected from the site. The fence was installed in NYSDOT Region 3, town of Preble, NY, in the southbound right of way of Interstate-81 at approximate reference marker 81I 3202 3094. The fence was installed in 2004, and has grown and functioned as expected since installation, preventing blowing and drifting snow from encroaching on the roadway in an area that was previously prone to frequent blowing snow problems.

Step 1: Determine Fence Orientation

Based on reports from snow and ice maintenance staff, and observations of drifts made during the site assessment phase, the snow fence design team determines the wind-angle relative to the road to be approximately 90° ($\alpha = 90$), indicating the fence should be oriented parallel to the roadway (Figure 10).

Step 2: Estimate the snowfall water equivalent (S_{we})

Using the site elevation of 364 m and latitude of 42° (measured using mapping software), the team estimates the snowfall water equivalent over the accumulation season (S_{we}) at the site:

$$S_{we} = (-695.4 + 0.076 * \text{Elev} + 17.108 * \text{Lat}) (0.0254) (0.10)$$

$$S_{we} = (-695.4 + 0.076 * 364 + 17.108 * 42) (0.0254) (0.10)$$

$$S_{we} = 0.129$$

Step 3: Measure Fetch Distance (F)

The team measures the Fetch using mapping software, and determines it to be 480 m (Figure 10).

Step 4: Calculate Snow Transport (Q)

The team uses the S_{we} and F values from Steps 2 and 3 to calculate the snow transport in tons per meter (t/m) at the site:

$$Q = (1500) (0.17) (S_{we}) (1 - 0.14^{F/3000})$$

$$Q = (1500) (0.17) (0.129) (1 - 0.14^{480/3000})$$

$$Q = 9 \text{ t/m}$$

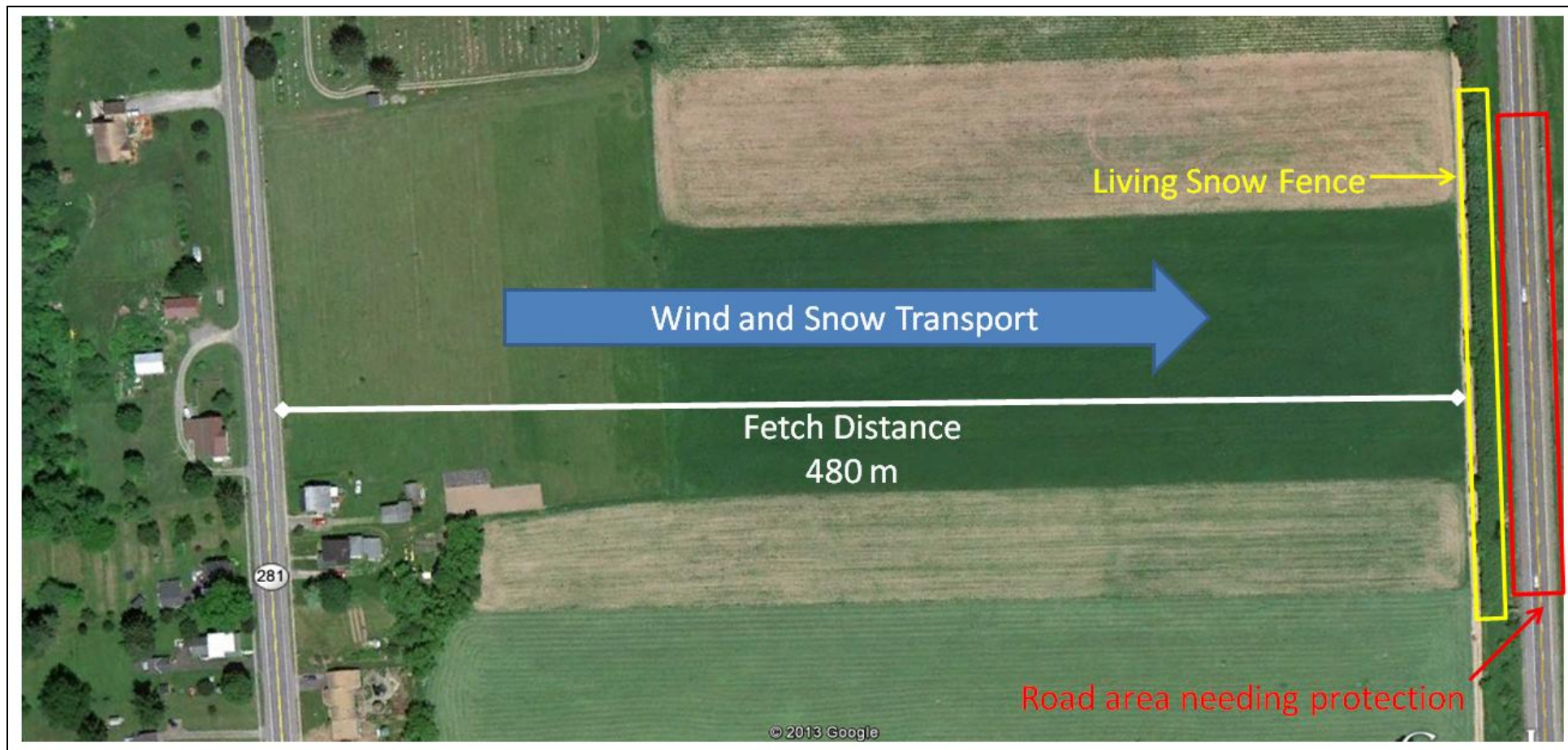


Figure 10 - Aerial photo of living snow fence site along Interstate-81 S in Preble, NY showing wind direction, fence orientation, and fetch distance. Diagram by SUNY ESF.



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Step 5: Calculate Required Height (H_{req})

The team uses the Q value from Step 4 to determine the required height (H_{req}) of the fence which is calculated at 1.0 m, indicating that the chosen species must grow to at least 1 m in height in a reasonable time frame.

$$H_{req} = (Q/8.5)^{0.455}$$

$$H_{req} = (9/8.5)^{0.455}$$

$$H_{req} = 1.0 \text{ m}$$

Step 6: Select a Species and design age (a)

The team decides to use shrub-willows for the snow fence. The team selects a design age of 7 years, when the fence is expected to be functional and nearing its full mature height. This is considered a good temporal starting point for analysis because the fence is likely to achieve partial or full functionality several years prior, but also live and function as a snow fence for at least another 10 - 15 years after this point with only minor changes in Height and Porosity.

Step 7: Estimate Optical Porosity (P) in the design age

The team chooses two fast-growing species of shrub-willow and decides to inter-plant them in two offset rows at the recommended spacing of 2 ft between plants, and 2.5 ft between rows. The team estimates that, with this planting pattern, porosity will be 40 percent (0.40) in design age of 7 years.

Step 8: Estimate Height (H) and Capacity (Q_c) in the design age

The team estimates that fence height in the chosen design age will be 6 m, and calculates the snow storage capacity using this height value and the Porosity (P) value from Step 7:

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

$$Q_c = [3 + 4(0.40) + 44(0.40)^2 - 60(0.40)^3] 6^{2.2}$$

$$Q_c = 402 \text{ t/m}$$

Comparing this Q_c output to the Q value from step 4, capacity is much greater than transport (Q_c = 44Q). This indicates that the drift length and appropriate setback distance will be reduced due to the large amount of excess storage capacity of the fence. Even if snow transport in a given winter is double the average (2Q), which is a 1 in 1000 winters occurrence (Tabler, 2003), the fence still has 22 times the storage capacity that is necessary, and the majority of snow transport will be stored upwind and in close proximity downwind of the fence.

Step 9: Calculate Setback Distance

Using the porosity (P) value from Step 7, the required height (H_{req}) from Step 5, and Q/Q_c values from Steps 4 and 8, the team calculates the downwind drift length (L) in design age seven:

$$L = \{[10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3\}(12 + 49P + 7P^2 - 37P^3)(H_{req})$$

$$L = \{[10.5 + 6.6(9/402) + 17.2(9/402)^2]/34.3\}(12 + 49(0.40) + 7(0.40)^2 - 37(0.40)^3)(1.0)$$

$$L = 9.4 \text{ m}$$



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The output of this equation indicates that the fence is expected to produce a drift length of 9.4 m in average winter at age seven. Even if the snow totals are double the average (2Q) in the snow season of age seven, the fence will still have large amounts of excess capacity, and the drift length will likely not be significantly longer than expected in the average winter. It is assumed that the fence will achieve some functionality prior to age seven, and also live at least 10 - 15 years beyond age seven, so the design team repeats steps 6 through 9 using design ages: 4, 10, and 15. The drift length output changes slightly with each design age as expected, and the team selects the final design age and corresponding setback distance that is most appropriate based on the estimates of drift length, existing and available right of way space for planting, and the long term snow and ice management goals for the site.

Note: The actual fence that this example is based on was planted on the far edge of the right of way boundary, at a setback distance of approximately 9.5 meters. The fence achieved functionality in the third winter after planting, and has since provided adequate protection of the roadway from blowing snow without drift encroachment onto the road.

Sources

Heavey, J.P. 2013. *Structure and function of living snow fences in New York State*. State University of New York -College of Environmental Science and Forestry. Syracuse, NY.

Tabler, R.D. 2000. *Climatological analysis for snow mitigation in New York State*. Tabler and Associates. Niwot, CO.

Tabler, R.D. 2003. *Controlling blowing and drifting snow with snow fences and road design*. Tabler and Associates. Niwot, CO.

Additional Resources

The New York State Department of Transportation (NYSDOT) and the State University of New York College of Environmental Science and Forestry (SUNY ESF) provide additional information relevant to the design of living snow fences on their web sites which can be accessed at the following web addresses:

www.nysdot.gov

www.esf.edu/willow

Materials available online include: additional fact sheets in this series, a species matrix for living snow fences, a cost-benefit model for living snow fences, and other informational and instructional materials.

J.P. Heavey & T.A. Volk
SUNY ESF, 2013

Fact Sheet 4 of 7

Species Selection

(4 pages)

Living Snow Fences

Fact Sheet Series - Fact Sheet #4

Living Snow Fence Species Selection



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Species Selection

Species selection is an important step in the design of effective and efficient living snow fences. A species matrix can assist in the plant selection for living snow fences by providing a palette of suitable species and a summary of relevant plant traits to compare and contrast species. A species matrix for living snow fences in New York State has been created in conjunction with these fact sheets. An abbreviated one-page version of the species matrix is provided at the end of this fact sheet. The full species matrix is available for download online at www.esf.edu/willow

Twenty-eight species suitable for living snow fences are included in the species matrix. The species suitable for living snow fences in New York State are mainly evergreen trees and deciduous shrubs that create fences with consistently low optical porosity from top to bottom. Species must be tolerant to a variety of roadside conditions across New York State and possess the other traits necessary to achieve adequate snow-trapping function. Every plant species is unique. The species matrix is intended as a selection tool to compare and contrast a variety of plants for living snow fences within the context of design goals and site conditions.

Plant Traits for Living Snow Fences

The morphological traits of height and optical porosity are the two most important factors influencing the function of living snow fences. Mature height should be at least eight feet to achieve adequate snow storage capacity. Porosity should be between 50 percent and zero percent (non-porous) near the base of the vegetation to prevent bottom gaps. Bottom gaps allow wind and snow to pass through, reducing the snow trapping function of the fence. Deciduous shrubs and evergreen trees are most suitable for expressing these traits in the landscape. Most species in this matrix have been proven suitable for living snow fences or windbreaks, but some species remain untested, as indicated on the first page of the full matrix. Additional physiological traits and ecological tolerances relevant to living snow fences have been included in this matrix to assist in plant selection. For example, plants with rapid growth rates are desirable to achieve functional heights and porosities as quickly as possible.



Norway spruce and white spruce living snow fence along Route 167 in Manheim, NY

Living Snow Fences

Fact Sheet Series - Fact Sheet #4

Living Snow Fence Species Selection



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Choosing a Species

A variety of factors should be considered when choosing a species for a living snow fence. A thorough analysis of the site conditions should inform the species selection to ensure plants will survive in the environmental conditions of the site. Tolerances to soil conditions and the potential stressors listed in this matrix can greatly affect the vigor and survival of the fence and the number of years until the fence reaches functional maturity. Choosing a species that is well suited to the environmental conditions of the site can greatly influence the success or failure of the fence. Multiple use considerations such as native status, ornamental flowers or value-added products can also be considered when choosing a species. The most widely tested and proven effective evergreen species for living snow fences in New York State are Norway spruce and white spruce. The most widely tested and proven effective shrub species for living snow fences in New York State are hybrid shrub willows.

Shrub-Willow Living Snow Fences

The shrub-willow cultivars included in the matrix possess many of the desirable characteristics for living snow fences such as sufficient height, porosity, and rapid growth rate. Shrub-willow living snow fences can be propagated from dormant stem cuttings with greater ease and at lower costs than using rooted stock of other shrub species. Shrub-willows also tolerate a variety of site conditions and are resistant to most pests and pathogens. Research on shrub-willow living snow fences is on-going. It is recommended that cuttings be purchased from a nursery to ensure quality. Additional information on shrub-willows is available at www.esf.edu/willow



Shrub-willow living snow fence along Route 30 in Grand Gorge, NY

Living Snow Fences

Fact Sheet Series - Fact Sheet #4 Living Snow Fence Species Selection



Northern white cedar living snow fence along Route 86 in Gabriels, NY



Snowdrift formed downwind of a three year old shrub-willow fence on Interstate 81 in Preble, NY

Additional Resources

Gullickson, D., Josiah, S.J., Flynn, P., 1999. *Catching snow with living snow fences*. University of Minnesota.

Tabler, R.D. 2003. *Controlling blowing and drifting snow with snow fences and road design*. Tabler and Associates. Niwot, CO.

Fact Sheet prepared for NYSDOT by:
J.P. Heavey & T.A. Volk
SUNY ESF, 2013

Living Snow Fences



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Fact Sheet Series - Fact Sheet #4

Living Snow Fence Species Selection

Scientific Name	Common Name	Growth Form	Growth Rate	Mature Height (ft)	Moisture Use	Fertility Requirement
<i>Amelanchier arborea</i>	serviceberry	Multi-stem shrub	Slow	36	Medium	Medium
<i>Caragana arborescens</i>	caragana	Multi-stem shrub	Rapid	12	medium	Low
<i>Cornus amomum</i>	silky dogwood	Multi-stem shrub	Moderate	10	High	Medium
<i>Cornus sericea</i>	red osier dogwood	Multi-stem shrub	Moderate	12	High	Low
<i>Corylus americana</i>	American hazelnut	Multi-stem shrub	Moderate	10	Medium	Medium
<i>Corylus cornuta</i>	beaked hazelnut	Multi-stem shrub	Moderate	15	Medium	Medium
<i>Ligustrum amurense</i>	Amur privet	Multi-stem shrub	Moderate	12	Medium	Medium
<i>Morella pensylvanica</i>	northern bayberry	Multi-stem shrub	Slow	12	Medium	Low
<i>Prunus americana</i>	American plum	Multi-stem shrub	Moderate	24	Medium	Medium
<i>Prunus tomentosa</i>	nanking cherry	Multi-stem shrub	Moderate	8	Medium	Medium
<i>Rhus glabra</i>	smooth sumac	Multi-stem shrub	Moderate	12	Low	Low
<i>Salix caprea</i>	shrub willow 'S365'	Multi-stem shrub	Very Rapid	20	Medium	Medium
<i>Salix eriocephala</i>	shrub willow 'S25'	Multi-stem shrub	Very Rapid	25	Medium	Medium
<i>Salix miyabeana</i>	shrub willow 'SX64'	Multi-stem shrub	Very Rapid	30	Medium	Medium
<i>Salix purpurea</i>	s. willow 'Fishcreek'	Multi-stem shrub	Very Rapid	25	Medium	Medium
<i>Salix sachalinensis</i>	shrub willow 'SX61'	Multi-stem shrub	Very Rapid	25	Medium	Medium
<i>Shepherdia argentea</i>	silver buffaloberry	Multi-stem shrub	Rapid	18	Medium	Low
<i>Syringa vulgaris</i>	common lilac	Multi-stem shrub	Moderate	20	Medium	Medium
<i>Vaccinium corymbosum</i>	highbush blueberry	Multi-stem shrub	Moderate	12	Medium	Medium
<i>Viburnum lentago</i>	nannyberry	Multi-stem shrub	Slow	28	Medium	Medium
<i>Viburnum prunifolium</i>	Blackhaw viburnum	Multi-stem shrub	Slow	16	Medium	Low
<i>Juniperus communis</i>	common juniper	Evergreen shrub	Slow	10	Low	Low
<i>Juniperus virginiana</i>	eastern red cedar	Single-stem tree	Slow	50	Low	Low
<i>Picea abies</i>	Norway spruce	Single-stem tree	Moderate	130	Medium	Medium
<i>Picea glauca</i>	white spruce	Single-stem tree	Slow	100	Medium	High
<i>Picea pungens</i>	blue spruce	Single-stem tree	Slow	100	Medium	Medium
<i>Taxus baccata</i>	English yew	Evergreen shrub	Slow	40	Medium	Medium
<i>Thuja occidentalis</i>	arborvitae	Single-stem tree	Slow	50	Medium	Medium

For complete living snow fence matrix and plant characteristics go to www.esf.edu/willow

Fact Sheet 5 of 7

Site Preparation

(5 pages)



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Site Preparation

After the site assessment and design phases, it is important to properly prepare the site before planting a living snow fence. Investing adequate time and resources in thorough site preparation will improve growth rates and long-term survival. Site preparation will minimize the time it takes for a living snow fence to become effective, and maximize the return on investment. The practices listed in this fact sheet are considered best management practices that can be applied to all types of living snow fences. This includes all species of evergreen trees and woody shrubs recommended for living snow fences. The site preparation tasks summarized here can be followed in the order they appear to achieve sufficient site preparation and improve the health and vigor of living snow fences. Roadside environmental conditions can be stressful to plants in a number of ways. Site preparation improves site conditions as much as possible to give living snow fences an advantage over competing species in stressful roadside conditions.

Step 1: Suppress existing vegetation

The first step in site preparation is to suppress and clear all vegetation that exists within and on either side of the planting strip. The planting strip should be at least 5 feet wide depending on the vegetation type and number of rows. Mow strips at least 8 feet wide should be established on either side of the 5 foot planting strip for a total width of cleared vegetation of at least 21 feet (see figures 1 and 2 next page). Vegetation should be suppressed with a combination of chemical and mechanical controls. A broad spectrum post-emergent herbicide such as glyphosate is an effective chemical control in most cases. Note that glyphosate will kill most living snow fence species and should only be used during the site preparation phase before vegetation is installed. Consult your local certified herbicide specialist and follow the instructions provided by the herbicide manufacturer. Most mechanical control can be accomplished by brush hogging. Trees and large shrubs can be removed with brush saws and chainsaws and then chipped. The flow diagram on the last page of this fact sheet provides a guide with several steps necessary to thoroughly suppress vegetation on and around the snow fence planting area.

Step 2: Rip sub-soil

Once the existing vegetation has been suppressed, the next step is to mechanically loosen the soil on the planting strip. Before ripping the subsoil, contact Dig Safely New York, or a similar organization in other states, to ensure no buried utilities are in the planned planting strip. Ripping will break up hardpans and compacted soils, allowing better root development for living snow fences. Use a chisel plough or ripping attachment to rip the sub-soil. Ripping to a depth of at least 12 inches is often required in right of way soils. More traditional agricultural tillage equipment may be sufficient if planting in soils that have been recently tilled for crops. Rip at least one or two complete passes up and down the length of the planting strip for each row of plants. For closely spaced plants, a single pass may be effective, but for more widely spaced plants and multiple rows, two or more passes per row should be completed.

Step 3: Amend soil based on soil analysis

Based on the lab analysis of soil chemical properties conducted in the site assessment phase, add the necessary soil amendments to the planting strip at the appropriate application rates. This may include lime to raise the pH, compost to increase organic matter or nutrients to improve fertility. Consult your local environmental specialist if you are unsure what soil amendments are appropriate for the chosen species and site conditions.

Living Snow Fences

Fact Sheet Series - Fact Sheet #5
Living Snow Fence Site Preparation

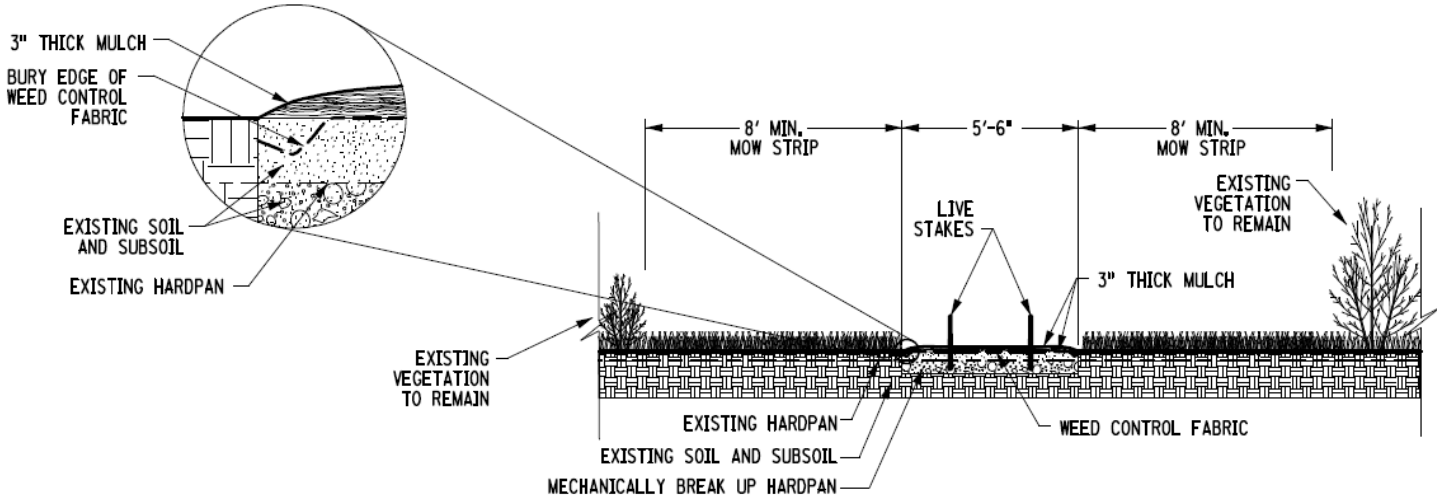


Figure 1 - Cross-sectional view of prepared willow snow fence site (not to scale). Adapted from NYSDOT, 2013.

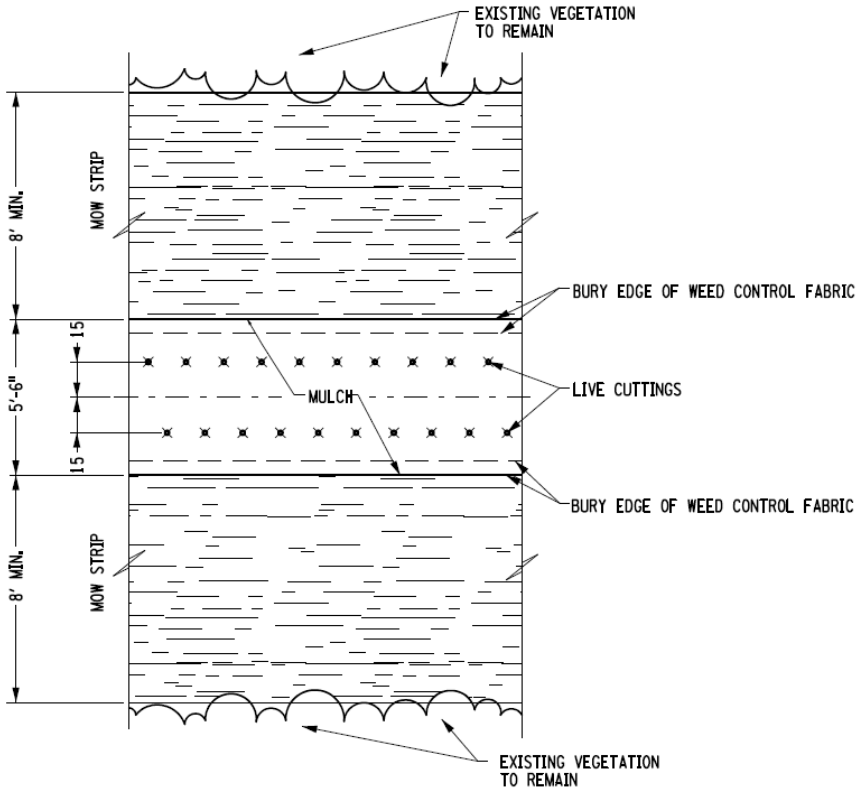


Figure 2 - Overhead view of prepared willow snow fence site (not to scale). Adapted from NYSDOT, 2013.

Living Snow Fences

Fact Sheet Series - Fact Sheet #5

Living Snow Fence Site Preparation



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Step 4: Cultivate topsoil

Use a rototiller or disking attachment to cultivate the topsoil on the planting strip. Cultivate the topsoil to a depth of 6 inches. Make at least three complete passes up and down the length of the planting strip to thoroughly break up the soil and incorporate amendments. Level and smooth the planting strip in the final pass to prepare the site for planting.



A planting strip is cultivated for a living snow fence on Route 12 in Paris, NY

Step 5: Evaluate the effectiveness of weed-control efforts

Some sites may have persistent perennial weed species that reproduce from roots, rhizomes, and other plant parts. These sites may require further chemical control after the planting strip is prepared. If the site is known to have persistent weed issues, or if a high percentage of weeds (>25 percent) are observed to grow back shortly after previous controls efforts, reapply a broad spectrum post-emergent herbicide to the planting strip, or cultivate the soil again and apply a pre-emergent herbicide, before proceeding to the next stage of site preparation. Be sure to allow sufficient time between herbicide application and planting. Allowing such time will ensure unwanted vegetation is thoroughly killed and the herbicides do not damage or kill any of the living snow fence plants. Consult your local herbicide specialist and follow the label instructions provided by the manufacturers.

Living Snow Fences

Fact Sheet Series - Fact Sheet #5

Living Snow Fence Site Preparation



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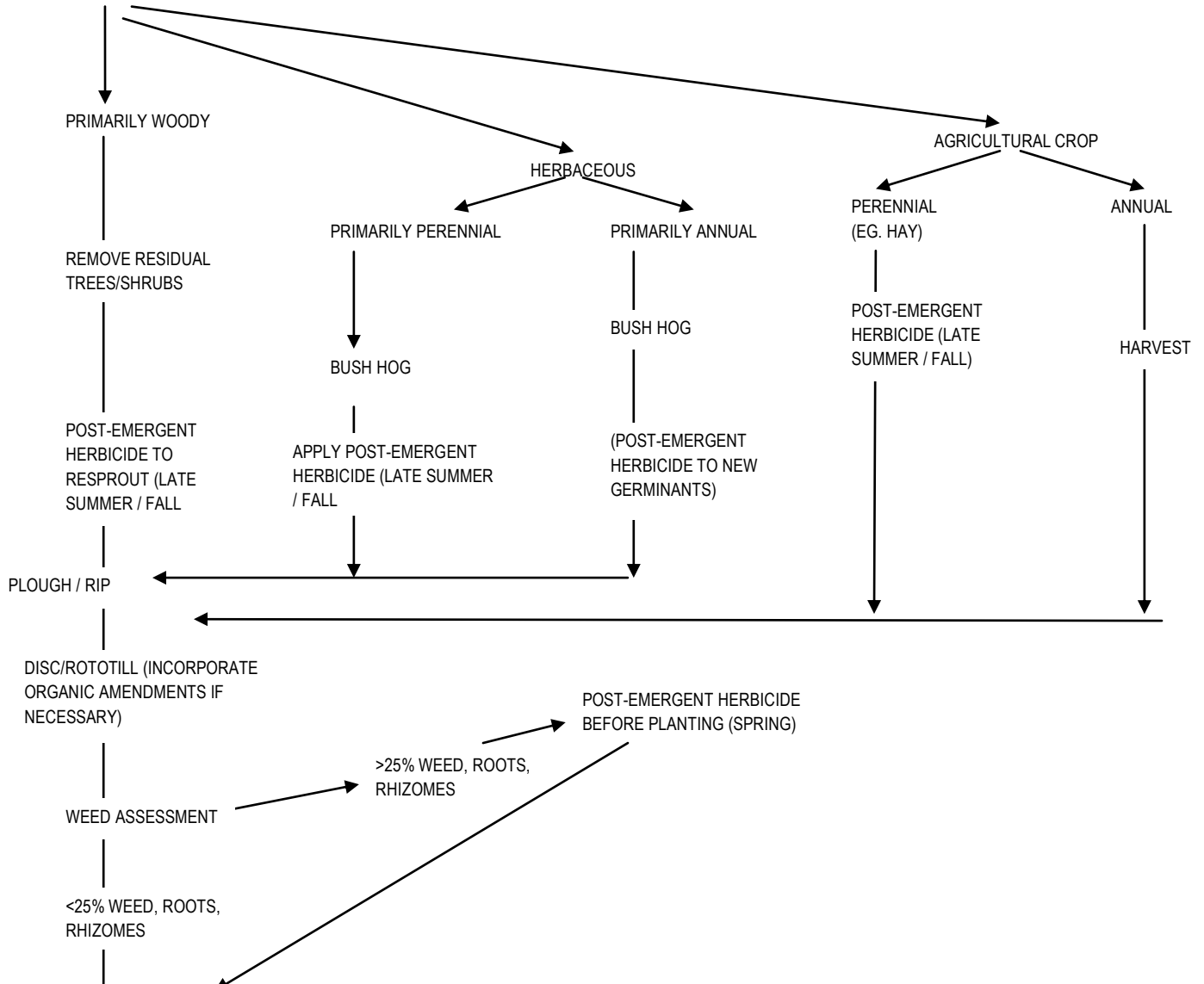
Step 6: Apply landscape fabric

Apply a biodegradable landscape fabric such as paper or plant fiber to the planting strip. Landscape fabric acts as a temporary weed barrier while young plants become established. Fabric should be wide enough to cover the planting strip with at least 1 foot of fabric on either side of trees after planting. Multiple strips of fabric should be used for wider planting strips. Fabric can be installed with a roller attachment to bury fabric edge as shown below. Use biodegradable fabric pins to secure the fabric to the ground at the beginning and end of each roll, and anywhere that the edge of the fabric is exposed to prevent the fabric from being lifted by the wind. Fabric can be applied without burying the edges, but a large number of biodegradable fabric pins will be required to temporarily secure all the edges until mulch is applied. In this case pins should be inserted on both sides of the fabric at 12 to 18 inch spacing to temporarily secure the fabric to the ground. Biodegradable fabrics buried under mulch may break down in a matter of months, but fabric should be rated to last for one or two seasons under mulch if possible. Synthetic landscape fabrics are not recommended for living snow fences because they have been observed to cause detrimental effects on trees in living snow fences, such as girdling, scorching, and poor root development. Likewise metal landscape fabric pins are not recommended for living snow fences because they are not readily biodegradable and can cause damage to maintenance or farming equipment such as mowers and tillers.



A paper landscape fabric is applied to a prepared planting strip using a roller attachment

- STEP 1: ASSESS OPERATIONAL LIMITATIONS OF THE SITE**
STEP 2: ASSESS EXISTING VEGETATION AND SOIL CONDITIONS AT THE SITE
STEP 3: CHOOSE AND IMPLEMENT A SITE PREPARATION PLAN



STEP 4: EVALUATE THE EFFECTIVENESS OF SITE PREPARATION. DID SITE PREPARATION...

- ADDRESS SITE LIMITATIONS IF POSSIBLE
- ACHIEVE EFFECTIVE WEED CONTROL
- CREATE SUITABLE SOIL CONDITIONS FOR PLANT GROWTH

INSTALL LANDSCAPE FABRIC
 PLANT LIVING SNOW FENCE
 IMPLEMENT FOLLOW-UP WEED-CONTROL STRATEGY
 (MOWING, HERBICIDES, MULCHES)

Diagram adapted from Boysen, B., and Stobel, S. *A Growers guide to hybrid poplar*. OMNR, Toronto Canada.
 Developed for living snow fences by T.A Volk, L.P. Abrahamson, and J.P. Heavey, SUNY ESF, Syracuse, NY, 2013.

Additional Resources

Gullickson, D., Josiah, S.J., Flynn, P., 1999. *Catching snow with living snow fences*. University of Minnesota.

Tabler, R.D. 2003. *Controlling blowing and drifting snow with snow fences and road design*. Tabler and Associates. Niwot, CO.

J.P. Heavey & T.A. Volk
 SUNY ESF, 2013

Fact Sheet 6 of 7

Planting

(5 pages)

Living Snow Fences

Fact Sheet Series - Fact Sheet #6

Planting Living Snow Fences



New York State
Department of Transportation



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Planting Techniques for Living Snow Fences

Two general categories of plant materials, rooted and unrooted, can be used for living snow fences. The planting techniques used with rooted plant materials are different from the techniques used with unrooted plant materials. Types of rooted planting stock include balled & burlapped (B&B), potted, bareroot, and seedlings. Types of unrooted planting stock include species that can be planted as single stem cuttings without pre-formed roots such as shrub-willows. Step by step planting techniques for both rooted and unrooted stock are provided in this fact sheet in the general order they should be preformed.

Planting Techniques for Rooted Stock

Rooted stock is used for planting evergreen trees and most shrubs. The following bullets and Figure 1 on page 2 outline a general protocol that can be followed for planting rooted stock:

- ◆ Obtain planting stock from a reputable nursery or plant supplier. Make certain that plants are healthy and vigorous. Inspect the roots, trunk, branches, and leaves of each plant for signs of damage, disease, pests, or lack of vigor. Reject any plants that appear to be damaged, diseased, or in poor health.
- ◆ Rooted evergreen trees can generally be planted at six to eight feet spacing between trees and rows. Rooted shrubs can generally be planted at three to four feet between plants and rows. Use species specific planting information as much as possible by consulting your local environmental specialist and the living snow fence species matrix available at www.esf.edu/willow
- ◆ After applying biodegradable landscape fabric to the planting strip, mark the plant and row spacing pattern on the fabric with spray paint to indicate the location that each plant will be installed. Open the fabric in each marked location by making an "X" shaped cut into the fabric that is large enough to dig a hole that will properly accommodate the root ball of the plant.
- ◆ Dig planting holes to twice the width of the root ball, and to a depth that will position the highest roots on the trunk approximately 1 inch below ground level and no deeper. Make the bottom of the hole level, and the sides of the hole vertical. Remove loose soil from the bottom of the hole after digging. Uncompacted soil at the bottom of the hole can cause the plant to shift after planting and negatively impact health and survival. If digging through multiple soil horizons (layers), keep the soil from each layer separate and backfill the layers in reverse order to maintain the natural soil profile.
- ◆ Keep plants well watered, in a shaded location until planting. Remove the container from the roots just before planting. Remove the containers and plant trees one at a time, completing all the steps of planting for each tree before moving on to the next one.
- ◆ Place the tree in the center of the hole, again making sure that the highest root on the trunk will be just slightly below ground level when filled in. If necessary, correct the hole to the appropriate depth by digging more, or backfilling soil to the bottom of the hole and firmly tamping it down to create a firm and level base at the bottom of the hole.

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Planting Living Snow Fences



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- ◆ Check the root ball for circling or compacted roots before planting. Loosen roots by hand, or with a cutting tool if necessary. Roots should be loose, pointing down and slightly outward, and evenly spread out in the hole as shown in example 12 of Figure 1 below. Refer to examples 1 through 11 in Figure 1 to avoid the many common planting mistakes associated with rooted stock.

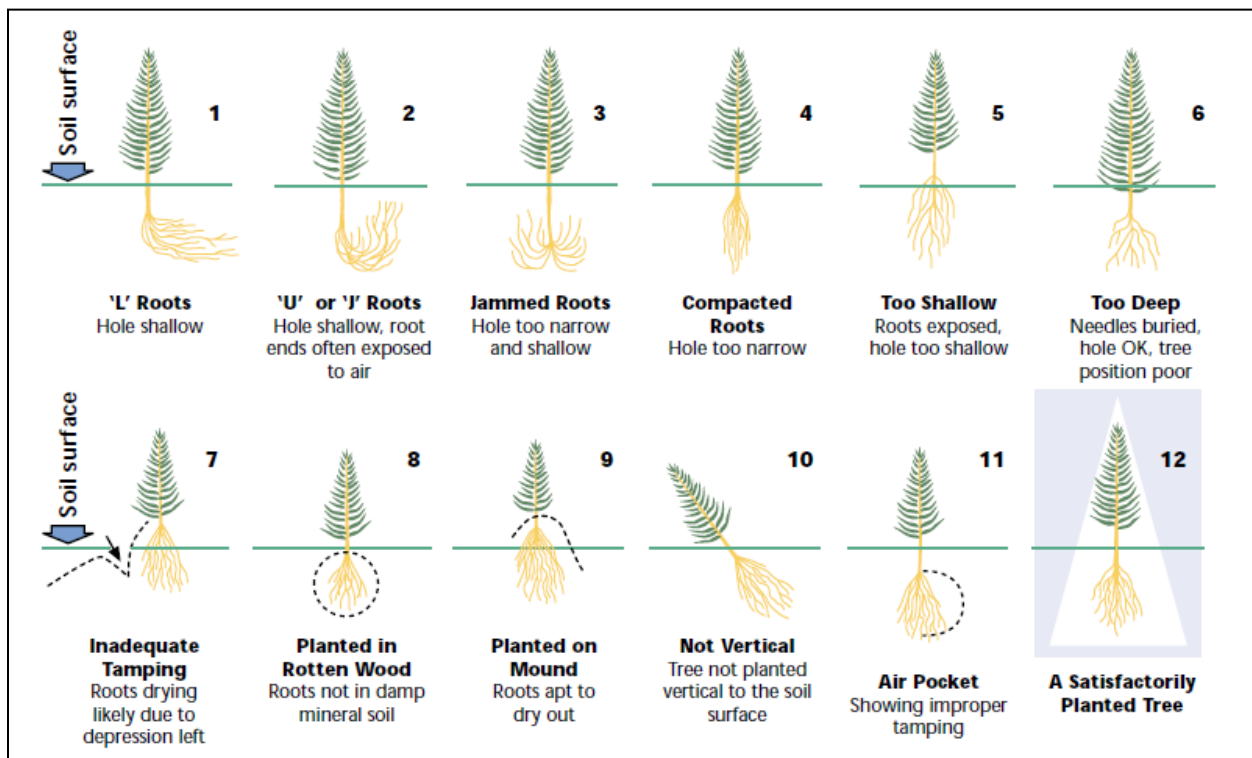


Figure 1 – Proper planting technique for rooted stock and common mistakes

Source: Pacific Northwest Extension (2005)

- ◆ Once the tree and its roots are correctly positioned in the hole, backfill soil around the roots while continuing to hold the tree in the correct position.
- ◆ Fill and firm the soil lightly by hand, until the hole is 75 percent full. Saturate the soil in the hole with water, wait for it to drain, then gently straighten or adjust the tree position if necessary. Firm the soil again, applying slightly more pressure.
- ◆ Backfill the rest of the hole with soil, again making sure that the position of the highest root is just below ground level when the tree is fully planted. Tamp the soil firmly around the hole with a tamper and water the tree again.
- ◆ Carefully apply clean wood mulch in a 3 inch layer on top of the landscape fabric around all the trees, leaving 6 inches on all sides around the trunk clear of any mulch or debris. Wood mulch should be

Living Snow Fences

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Planting Living Snow Fences



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fresh and clean with a coarse grind; free of soil, weeds, grass, etc. Dirty, composted, or shredded wood mulch will allow weeds to germinate in the planting strip and should be rejected. Mulch can be applied on or near the planting strip using a tractor or bucket loader, and then carefully spread around the inserted plants with shovels and hard rakes.

- ◆ Large rooted stock may require staking on very windy sites, but staking is generally not required when proper planting techniques and quality planting stock are used. Rooted stock may require periodic watering during the first growing season until plants become established, especially in the first few weeks after planting.

Planting Techniques for Unrooted stock

Single stem cuttings of shrub-willows and select other shrub species can generate new roots and stems when planted directly in to the ground. This makes the planting process less costly and easier to manage relative to planting rooted stock. The following bullets outline a general protocol that can be followed in the order presented for successfully planting unrooted stock:

- ◆ Twenty-inch long stem cuttings are recommended for living snow fences under most planting conditions (Figure 2 and 3). Obtain 20-inch cuttings of species suitable for living snow fences in New York or the Northeast from a reputable nursery or plant supplier to ensure quality of the cutting and viability once planted. Refer to the species matrix for living snow fences available at www.esf.edu/willow for a list of suitable species. Store cuttings in sealed plastic bags at temperatures just below freezing until the day of planting. After removing cuttings from cold storage, keep them sealed in bags and boxes in a shaded location until the time of planting to retain moisture and viability. Do not leave sealed bags with cuttings in the sun; this will cause them to heat up rapidly and lose viability.



Figure 2 - Bundle and close up image of unrooted 20" shrub-willow stem cuttings for planting.

Photos by NYSDOT and SUNY ESF

Living Snow Fences

Fact Sheet Series - Fact Sheet #6 Planting Living Snow Fences



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- ◆ Mark the plant and row spacing pattern on the applied landscape fabric with spray paint to show the location where each plant will be installed. The recommended spacing for shrub willow fences is 24 inches between plants and 30 inches between rows. Rows should be offset so that there is one plant per foot along the double row (Figure 3). With proper maintenance, this planting pattern will grow into a dense snow fence with no gaps. Using two or more intermixed species per fence is recommended to create diversity in the planting. Refer to Fact Sheet #5 in this series for a diagram of the planting pattern described here.
- ◆ Insert cuttings by hand or lightly tap them into place with a rubber mallet. Plant the cuttings vertically, making sure the buds are pointing up (Figure 4). Plant the cutting to a depth of 7 - 12" below the soil. Close the hole around each cutting by firming the soil at the base of the cutting with your hands or the heel of your boot. The planting window for shrub-willow in New York State is late April through early June. Plantings done after this window will be prone to failure due to high temperatures and insufficient soil moisture.



Figure 3 (left) – Willow cuttings installed through paper landscape fabric in a double row pattern
Figure 4 (right) – Willow cuttings planted to the proper depth with the buds facing upwards
Photos by SUNY ESF

Living Snow Fences

Fact Sheet Series - Fact Sheet #6 Planting Living Snow Fences



- ◆ After planting, apply clean wood mulch around to the cuttings in a three inch layer, leaving five to eight inches of the cutting exposed above ground (Figure 5). In some cases, if a paper landscape fabric and light textured wood mulch is used, cuttings can be planted through the mulch and paper fabric using parallel tape measures to set the planting spacing (Figure 6). Be certain this technique will work and that cuttings will go through both mulch and paper without bending the cutting before applying mulch to entire planting strip.



Figure 5 (left) – Applying wood mulch to a planted shrub-willow snow fence
Figure 6 (right) – Planting cuttings directly through mulch and landscape fabric underneath
Photos by SUNY ESF

Sources and Additional Resources

Gullickson, D., Josiah, S.J., Flynn, P., 1999. *Catching snow with living snow fences*. University of Minnesota.

Pacific Northwest Extension, 2005. *Trees against the wind*. Pacific Northwest Extension, PNW005.

Tabler, R.D. 2003. *Controlling blowing and drifting snow with snow fences and road design*. Tabler and Associates. Niwot, CO.

J.P. Heavey & T.A. Volk
SUNY ESF, 2013

Fact Sheet 7 of 7

Maintenance

(4 pages)



Living Snow Fence Maintenance

Living snow fences require care and monitoring for several years after planting. The length and type of care varies based on the plant species, site conditions, and the quality of site preparation. Once plants are well established and have achieved sufficient height growth, care and monitoring can be reduced or eliminated. Plants of the same age and height are needed for effective and continuous snow control along the roadway. Monitoring of snow fences is essential so that problems with dead or slow-growing plants are quickly identified and solutions can be developed and enacted. Some potential problems to watch for and potential solutions for addressing them are listed below.

Weeds and Competing Vegetation

Competition from weeds and other vegetation is often the primary threat to the establishment and optimal growth of newly planted living snow fences. Weeds must be monitored and controlled for two to three years after planting, to reduce competition for water, sunlight, and nutrients. Proper site preparation is the first step to stopping weeds from encroaching on the planting strip. This includes the use of herbicides, tilling, establishing mowed strips on either side of the fence, landscape fabric, and mulch as described in fact sheets #5 "Site Preparation", and #6 "Planting" of this series. After planting, maintaining 8 ft. wide mowed strips on either side of the fence is the first line of defense against weed encroachment (Figure 1). These strips should be mowed at least three times per season.

One of the most effective preventive practices for weed control is using a consistent three inch layer of clean wood mulch across the entire planting strip. Wood mulch should be fresh; have a coarse grind; and be free of all soil, weeds, grass, plant parts, etc. Dirty, composted, or shredded wood mulch will allow weeds to germinate in the planting strip and should be rejected. Using adequate amounts of clean mulch will greatly reduce the amount of maintenance needed in the first few years after planting.

Weeds and other vegetation may become established on the planting strip despite the best site preparation techniques. If a high percentage of weeds (>25 percent of ground cover) become established on the planting strip before the snow fence is well established, further weed control efforts should be undertaken. This may include a combination of using brush mowers, herbicides, hand weeding, or more mulch. Extreme care must be taken when controlling weeds on the planting strip after the fence is installed. Mechanical controls must not damage plant stems or roots. Herbicides must be carefully selected to target only weeds and not the snow fence species. Consult your local herbicide and environmental specialist to develop and implement a weed control plan if a high percentage of weeds become established any time in the first three years after planting.

Wildlife

Browse damage from wildlife is a common challenge with roadside vegetation including living snow fences. Local wildlife patterns, palatability of selected species, and abundance of other preferred food sources should be considered during the site assessment and design phases. Heavy browse can kill plants or severely slow down establishment if it is not promptly addressed. Deer and other species will browse on young shoots of nearly every species recommended for living snow fences (see Living Snow

Living Snow Fences

Fact Sheet Series - Fact Sheet #7

Living Snow Fence Maintenance



New York State
Department of Transportation



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Fence Species Matrix at www.esf.edu/willow). Long strips of palatable browse in the form of a living snow fence can provide an optimal food source, especially if browsers are not discouraged in any way. Maintaining mowed strips 8 feet or wider can reduce the amount of cover and habitat for browsers and discourage their presence. Shrubs and evergreen trees can be sprayed with natural deer repellent (Figure 1) which works well in preventing browse. Temporary fences can be established around young plants in cases of extreme browse. These measures can temporarily deter browsing long enough for fences to reach heights at which they will be less susceptible to browse.



Figure 1- Maintaining 8+ feet wide mowed strips on either side of the fence, and regularly applying deer repellent to the fence were effective weed and browse controls on this 1 year old shrub-willow snow fence on Route 10 in Beerston, NY. Photo by SUNY ESF

Weather Damage

As in nature, occasional disturbances to trees and plants from weather events are inevitable. Wind, hail, drought, flooding, ice storms, thunderstorms, snow deposition, freeze/thaw cycles, and other adverse weather conditions can damage or kill living snow fences, especially when they are young. Monitor new installations for weather damage, especially after severe weather events. Weather is uncontrollable and often unpredictable, but plants can sometimes be protected before severe weather and rehabilitated or quickly replanted after a severe weather event.

Living Snow Fences

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Pests & Diseases

Living snow fences are organisms in nature, susceptible to parasites and other biological disturbances. Insects, fungus, viruses, and other pests can severely damage and kill plants. Planting disease resistant species is the best approach to this challenge. A keen eye and knowledge of plant pathology, entomology, and vegetation management may be necessary to properly identify and mitigate pest and disease problems. If a suspected pest problem is encountered, consult your local environmental specialist for advice on how to best manage the problem. For shrub-willow fences, Cornell University has produced a series of fact sheets on the most common pests and diseases that is available online at http://willow.cals.cornell.edu/Resources/fact_sheets.html



Cytospora canker found on an 8 year old shrub-willow living snow fence along Interstate-81 in Preble, NY
Photo by SUNY ESF

Maintenance

In addition to monitoring and mitigating stressors described above during the early stages of plant establishment, some standard maintenance is usually required for living snow fences to achieve optimal growth rates. As with monitoring for disturbances, once plants become established maintenance needs are reduced or eliminated. Standard maintenance considerations are described below.

Irrigation

Living snow fences planted using rooted stock should be provided with adequate water during the installation process, immediately after, and periodically over the first growing season in the absence of regular rainfall. Irrigation is generally not necessary in the case of shrub-willow snow fences, except in cases of extreme drought shortly after planting.

Living Snow Fences

Fact Sheet Series - Fact Sheet #7

Living Snow Fence Maintenance



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Replanting

Even with the best planning, site preparation, planting techniques, and growing conditions, 100 percent plant survival is unlikely. Replanting deceased or severely lagging plants in the first three growing seasons should be considered a routine maintenance task that is included in the initial plans and budget of a snow fence installation. Gaps in the fence created by lagging or deceased plants will decrease functionality and create channelized winds and drifting. It is important to replace deceased plants as quickly as possible to maintain an even-aged fence. Monitoring the fence regularly and replacing die-off as soon as possible is an important maintenance routine in the first three growing seasons. If dieback is observed early in the growing season, fences can be replanted that year. If dieback occurs later in the year, plan to replant any failed sections in the early spring of the second growing season.

Fertilizer

Fertilizers are generally applied in the site preparation phases or in the late spring of the second growing season. Fertilization may not be necessary and should be done selectively based on laboratory analysis of soil chemical properties that are tested during the site assessment phase (see Fact Sheet #3 in this series). Slow release fertilizers can be applied to the planting strip as a top-dressing to ensure optimal growth rates. Before applying fertilizers, be sure to verify that the installation site is not in an environmentally sensitive watershed where fertilizer use is regulated.

Coppicing

For shrub-willows and other coppice species, coppicing after the first year of growth is recommended to promote the re-growth of more stems, which results in lower optical porosity and increased effectiveness of the snow fence. Cut stems back during the dormant season (after leaf-fall) to a height of approximately 4-6 inches using a brush saw, sickle bar mower, or other mechanical cutting device that makes a clean cut and does not rip the plant's root system out of the ground. If possible, cut the plant above the point where new side branches attach to the main stem. This will encourage more sprouting from the side branches. If side branching begins higher up on the plant, the cut may be made up to 12 inches above the ground to maintain the side branches, but no higher. Coppicing is recommended in the fall as opposed to the spring, as heavy snow loads in the first winter can detach tender stems from the stump.

Additional Resources

Gullickson, D., Josiah, S.J., Flynn, P., 1999. *Catching snow with living snow fences*. University of Minnesota.

Tabler, R.D. 2003. *Controlling blowing and drifting snow with snow fences and road design*. Tabler and Associates. Niwot, CO.

Abrahamson et al. 2010. *Shrub willow biomass producers handbook*. SUNY ESF.

<http://www.esf.edu/willow/documents/ProducersHandbook.pdf>


J.P. Heavey & T.A. Volk
SUNY ESF, 2013

Task 2-A: Training Documents

Task 2-A: Training Documents

Overview: The deliverable for this task was a set of instructional presentations for training staff in the design and installation of living snow fence. Slides created for this purpose are included here, and followed by a series of class speaker instructional notes.

NYS DOT Living Snow Fence Training

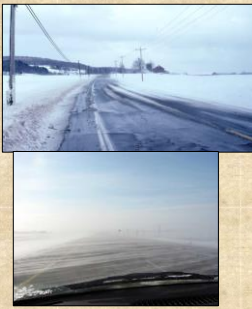


T. A. Volk, L.P. Abrahamson, P.J. Castellano, J. Heavey
 State University of New York College of Environmental Science and Forestry
 Utica NY, October 20, 2011.



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The Challenge




- Snow and ice removal and control costs over \$2 billion annually in the US
- NYSDOT annual S&I costs are \$252 million
 - \$154 million labor
 - \$38 million equipment
 - \$60 million materials
- Blowing and drifting snow causes:
 - Reduced visibility
 - Impaired road conditions
 - Reduced road width
 - More frequent road closures
 - Increased number of accidents and injuries
 - Increased need for plowing and deicing materials

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The Challenge



- Mechanical snow removal costs up to 100 times more than trapping snow with snow fences (SHRP 1991)
- Options
 - Wood, plastic or other structural snow fences
 - Living snow fences
 - Modify highway design

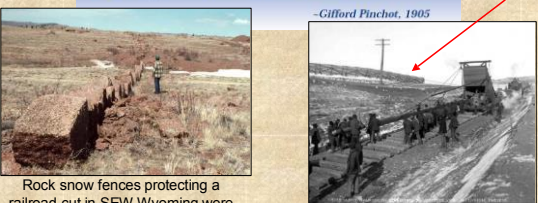
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Historical Use of Snow Fences

The forest acts powerfully in checking the force of the winds because the elastic swaying of the twigs and branches is a very effective hindrance to the movement of air.

– Gifford Pinchot, 1905




Rock snow fences protecting a railroad cut in SE Wyoming were probably built in 1868 (Tabler 2003)

Snow fences protecting the Union Pacific Railroad in 1901 (Tabler 2003)

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Structural snow fences




- Less costly than snow removal
 - Snow removal costs about \$3/ton (Tabler 2003)
 - A 4 ft high snow fence can trap up to 4.2 tons of snow per linear ft
 - That is >24,000 tons per mile
- Temporary or permanent
 - Wood or plastic composite
 - Cost varies with material and installation location
- Visually unappealing

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Temporary Structural Snow Fences



- In areas with large snow transport loads, temporary structural snow fences can become buried and ineffective

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A Solution – Larger Structural Fences



- Permanent structural snow fence being tested in the town of Scott
- Sometimes challenging to properly design and locate permanent snow fences with limited rights of way

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A Solution – Larger Structural Fences




- Permanent structural snow fence in western NY

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A Solution – Larger Structural Fences



Snow fences in Wyoming (Tabler 2003)

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Another Solution - Living snow fences

- Designed plantings of trees, shrubs, and/or native grasses that are strategically established short distances upwind of area of concern used to control drifting snow
- Key characteristics for suitable species
 - High density that extends to the ground
 - » Many deciduous trees do not have this form and are ineffective for snow fences
 - » Woody shrubs and evergreens are most favorable
 - Rapid growth
 - Suited to local soil and climate conditions
 - Easy to establish and maintain

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ESF **Living Snow Fences - Benefits**



- Over the long term they can be cheaper than plastic or wood snow fences
- Effective in years with heavy snowfall once established
 - Challenge: young living snow fences can be damaged by heavy snow accumulation
- Potential to provide wildlife habitat
 - May be a benefit or limitation
- Potential for income generation for landowner from materials produced from shrubs and trees
- Opportunities for carbon sequestration
- Difficult to capture benefit of externalities at this time

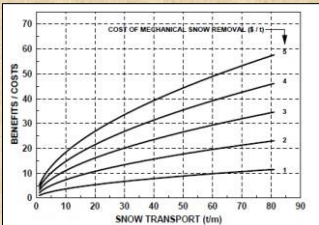
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ESF **Economic Benefit**

- Cost benefit ratio of living snow fences in MN ranged from 2:1 to 36:1 (Gullickson et al. 1999)
 - Used average snowfall (32 inches)
 - \$1/ton snow removal (it can be \$3/ton or greater in severe storms)
 - Only benefits related to snow removal were used as benefits
 - Benefits would be higher if road closure and accident reductions were accounted for
 - Ratios may also be improved with more efficient installation & maintenance practices
- Will develop a benefit ~ cost model for conditions in NY as part of this project

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ESF **Structural Snow Fences – Cost Benefit**



- Benefit cost ratio will increase as the amount of snow transported increased and the cost of removal increases

Benefit cost ratio for snow fences as a function of average annual snow transport and cost of snow removal (Tabler 2003)

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ESF **Economics of Living snow fences**
(Daigneault and Batters 2000)

	Three row living snow fence ¹	Double row slatted snow fence
Establishment (\$/mi)	20,400	16,366
Maintenance (\$/mi/yr)	1,000	8,700
Useful Life (yrs)	50	8
Total Net Benefits (\$)	1,246,000	110,000
Benefit: Cost ratio	6:1	2:1

¹ Two conifer and one shrub row, requiring 20 years to be effective. Estimated establishment for one row willow snow fence in a corn field was \$3,000/mi with annual maintenance cost of \$250/mi. Can be effective in 2 – 3 years.

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ESF **Living Snow Fences - Limitations**



- Traditional living snow fences require 6 – 20 years to become effective (Tabler 1994)
 - Address with choice and size of plants and design of system
- Require more space than structural snow fences because they often require more than one row of plants
- Biological systems – more care need to establish, potential for damage from pests and diseases
- They are permanent installations so sometimes it is harder to get landowner cooperation

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ESF **Potential Solution – Willow Snow Fences**



- A single or double row of densely planted shrub willows
 - Easier and cheaper to establish
 - Rapid growth
 - Dense canopy and lots of stem near the ground
- May not meet expectations of landowners and community
 - Mix with other species if desired
- Shrub willow research at SUNY ESF since 1986
 - Excellent knowledge base of willow growth, development and management
- Numerous crossbred varieties have been developed that are ideal for roadside applications

Mature single row willow snow fence in central NY

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Keys for Success



Willow snow fence two years after coppicing

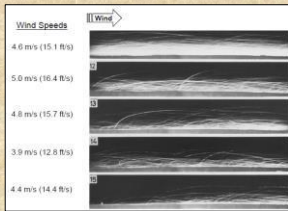
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- Collaboration with multiple agencies and landowners
- Planning and design in advance
- Proper site preparation
- Careful planting and maintenance

Principles of Blowing and Drifting Snow and Effect of Snow Fences



Snow Transport



Saltating snow particles (Tabler 2003)

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- Snow particles range in size from very small up to about 0.5 mm
- Main methods of movement are creep, saltation and turbulent diffusion
- Fluffy snow begins to move at ~15 mph
- Hardened snow may not move at 55 mph
- Most snow no longer moves below 15 mph



Snow Transport



Snow waves formed by creeping snow (Tabler 2003)

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⑦ Creep

- Particles too large to be lifted by the wind roll across the surface forming snow waves
- Snow waves largely disappear when winds are over (?) 35 mph because snow is picked up and moved
- Accounts for about 1/4 of snow movement at lower wind speeds
- Easily trapped by snow fences or topographic features



Snow Transport



Snow shadow created by 1.2m wide cylindrical shed (Tabler 2003)

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- Saltation
 - Lighter particles jumping across the surface but too heavy to remain suspended in the air
 - Most particles remain within a few inches of the surface
 - Can dislodge other particles when they land
 - Form snow streams in topographic depressions
 - Snow shadows form behind fixed features on the landscape because they deflect and disrupt the flow of particles



Snow Transport

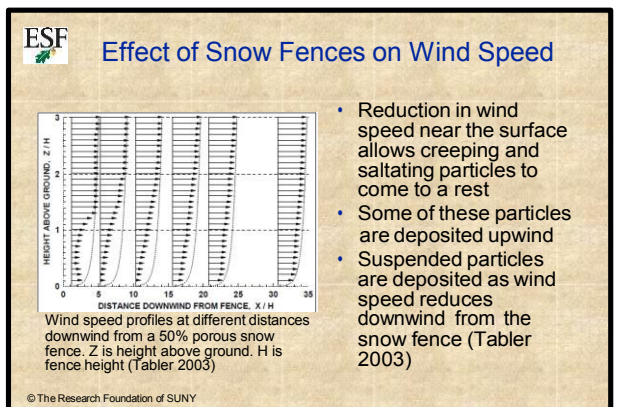
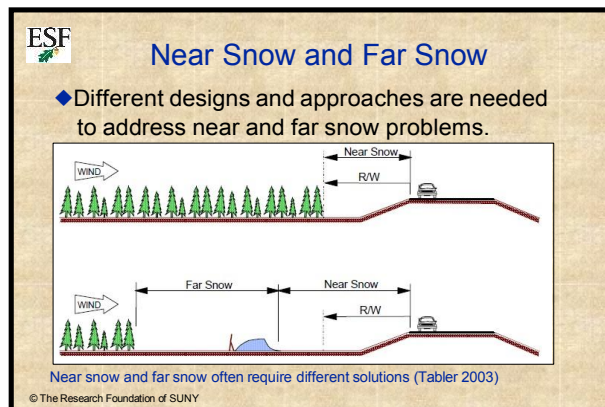
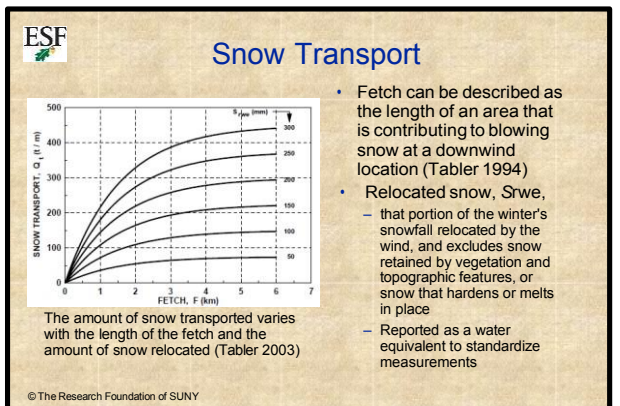
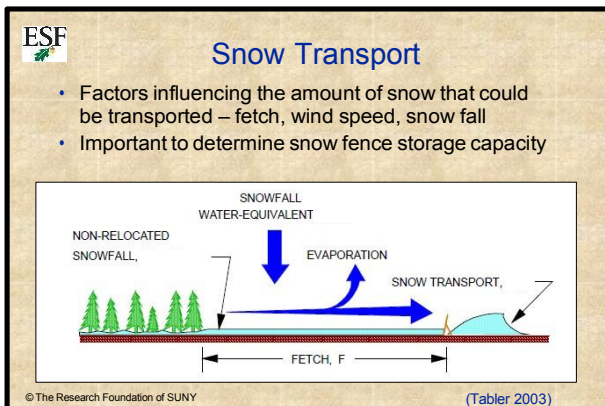
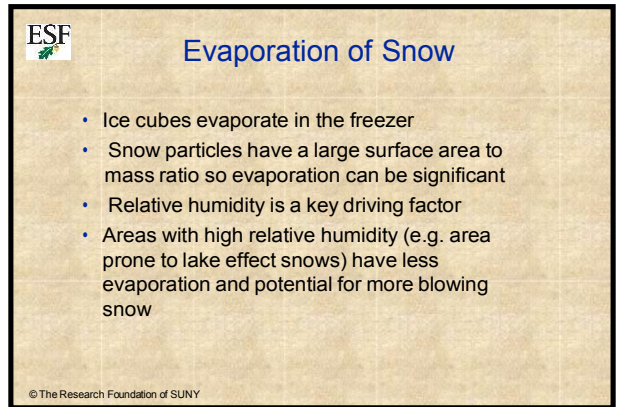
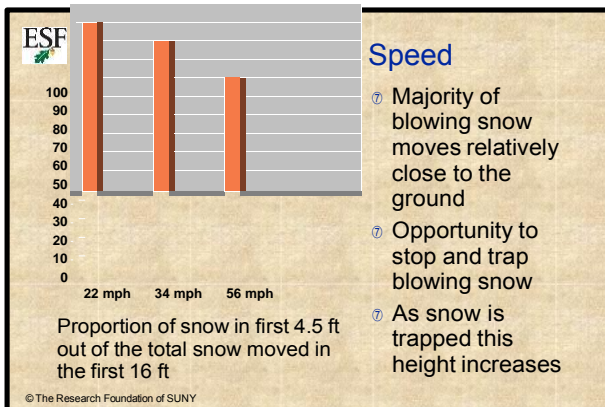


Turbulent diffusion of snow particles (Tabler 2003)

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⑦ Turbulent Diffusion

- Snow particles are suspended in the air without contact with the surface
- Smaller particles than saltation
- Most blowing snow is moved by turbulent diffusion
- Greatest proportion of total suspended snow is contained about 3 ft above the surface
- Significant transport ceases at 16 ft above ground level



How Snow Fences Work

- Snow fences redirect and change wind speed
 - Wind speed increases over the top and around the sides of the barrier
 - Wind speed is reduced below the top of the barrier and downwind, from the snow fence

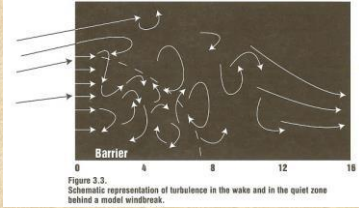
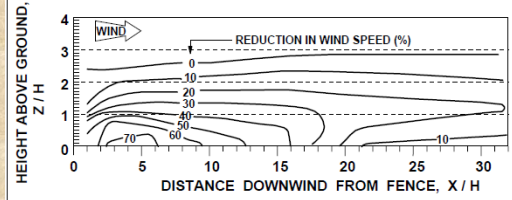


Figure 3.3. Schematic representation of turbulence in the wake and in the quiet zone behind a model windbreak.

(Gullickson et al. 1999)

Effect of 50% Porous Snow Fence on Wind Speed



(Tabler 2003)

- Wind speed reduction is roughly scaled with height
- When snow first begins to accumulate, the effect of the snow fence on wind speed controls how snow is deposited
- This changes as the snow drift develops and begins to influence air flow behind the snow fence

Snow Drift Development

- Snow drifts develop in stages over time
- Main components of snow drifts are shown below
- Equilibrium slope is reached only when snow fence is full

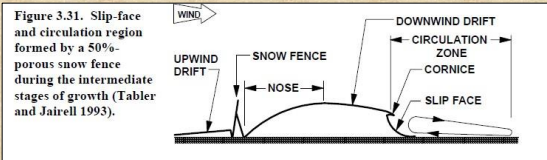


Figure 3.31. Slip-face and circulation region formed by a 50%-porous snow fence during the intermediate stages of growth (Tabler and Jairell 1993).

(Tabler 2003)

Snow Drift Development

- Initial stage – wind speed reduced and snow falls to about 7H
- Forms lens shaped drift that becomes thicker extending the effective sheltered region to 12 – 15H until fence is ~75% full
- Slip face and circulation zone develop, which extends 6 – 7H
- With light winds, trapping efficiency is still good
- With newly fallen snow the particles can adhere and form a cornice

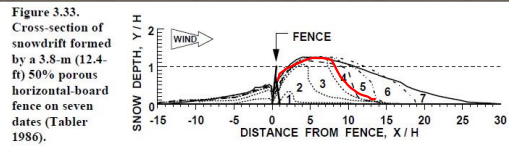


Figure 3.33. Cross-section of snowdrift formed by a 3.8-m (12.4-ft) 50% porous horizontal-board fence on seven dates (Tabler 1986).

Snow Drift Development – Stage 3

- As snow drift depth reaches its maximum (1.0 – 1.2H for 50% porous snow fences) snow begins to fill the circulation zone and drift lengthens downward (measurements 4–6)
- As long as slip face is present, trapping efficiency is fairly high

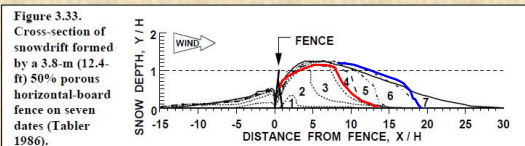


Figure 3.33. Cross-section of snowdrift formed by a 3.8-m (12.4-ft) 50% porous horizontal-board fence on seven dates (Tabler 1986).

Snow Drift Development – Stage 4

- Drift develops a smooth surface with no slip face or circulation zone
- Drift extends to about 20H
- Trapping efficiency declines and only creeping and saltating particles are trapped
- Growth is slow but can extend out to 30 – 35H
- Equilibrium drift is streamlined and zero trapping efficiency

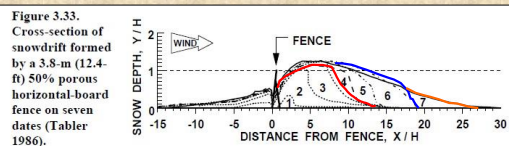


Figure 3.33. Cross-section of snowdrift formed by a 3.8-m (12.4-ft) 50% porous horizontal-board fence on seven dates (Tabler 1986).



Snow Drift Development in NY

- Hypothesis: Lower relocation coefficients, denser snow, shorter accumulation seasons, smaller fetches, more obstructions limit the amount of potential snow transport in the Northeast
 - Fences in New York may never reach equilibrium
 - Very tall willow and evergreen fences with high densities are therefore probably "oversized" in terms of storage capacity
 - If correct, this indicates fences can be sited closer to roadways than the standard equations and trends would dictate because earlier drifts stages and larger windward drifts have enough capacity to handle potential transport
 - Will test this by measuring snow drifts behind living snow fences in NY

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Snow Drift Development (Double Row of Shrub Willow Two years after Coppicing)



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Snow Drift Development



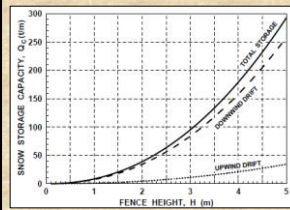
- Potential snow storage is related to the height of the snow fence
- Doubling the height of the snow fence increases snow storage potential by 4x assuming all other factors are equal

Snow storage capacity of structural snow fences can become filled making them ineffective

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Snow Storage vs. Height 50% Density Structural Snow Fence



Snow storage capacity in upwind and downwind drifts formed by a Wyoming snow fence (Tabler 2003)

- Snow can be stored upwind and down wind from snow fences
- For 50% density shown here the amount of snow stored upwind is relatively small
- As density increases the amount of upwind snow stored increases

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Snow Storage vs. Height 50% Density Structural Snow Fence

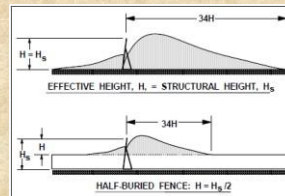
Fence Height (ft)	Tons of snow/linear ft.
4.0	4.4
4.5	5.7
6.75	14.0
8.0	20.3
10.0	33.1
12.0	49.5
15.0	79.0

(Tabler 2004)

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Snow Fence Height



Effective height (H) of a snow fence is important in determining the size of the drift and the amount of snow stored (Tabler 2003)

- All other things being equal, the equilibrium snow drift dimensions are proportional to the effective height of the snow fence
 - e.g. a drift behind a 8 ft fence is twice as long and twice as deep as a 4 ft fence
- Effective height is the height of the snow fence above the surrounding snow cover

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ESF **Snow Drift Development**
(Double Row of Shrub Willow Two years after Coppicing)

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ESF **Edge or End Effect**

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ESF **Edge or End Effect**

- Areas of turbulence are created around the ends of snow fences creating areas for potential snow drifts
- Length of drift is reduced by rounding effect at the ends of snow fences
 - reduces storage capacity and snow trapping efficiency
- Extend snow fence beyond the area that needs to be protected

(Tabler 2003)

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ESF **Edge or End Effect**

- Fences can be parallel to the road if the prevailing wind is within 35° of being perpendicular (attack angle >55°)
 - Living snow fences are 3D so they may be effective at a smaller attack angle
- Proper extension of the snow fence is more important than the orientation

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ESF **Snow Fence Density / Porosity**

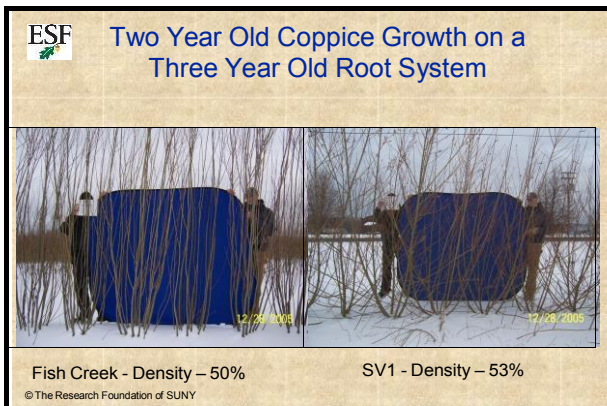
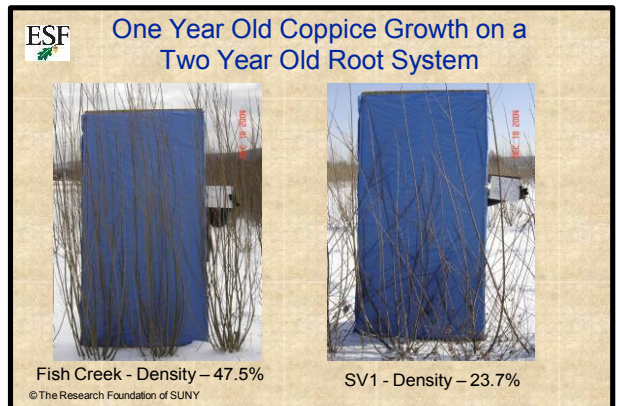
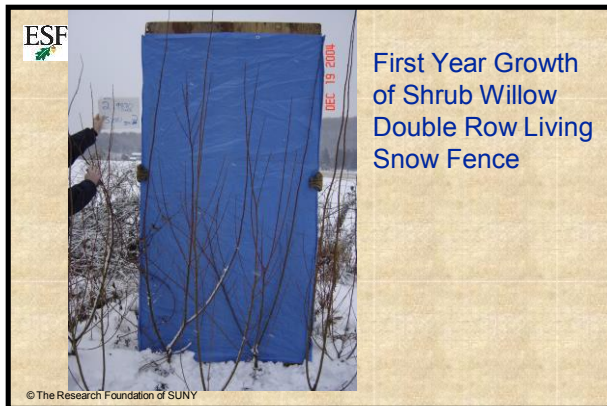
- Snow fence porosity affects ability to trap snow and the shape and size of an equilibrium snow drift change
 - Solid fence has larger drifts on the upwind side and smaller drift down wind
 - Snow fence density of 50 – 60% (porosity of 50 – 40%) has the greatest storage capacity

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ESF **Snow Fence Density / Porosity**

- Changes in porosity has an effect on the size and length of the equilibrium snow fence
- Challenge for living snow fences because porosity changes as the plants develop

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Identifying the Problem

- The first step is to identify the problem
 - Drift encroachment on the road
 - Poor visibility for drivers
 - Slush and ice formation
 - Combination of problems
- What impact does this have on accidents, crew requirements, duty cycles, road closures etc.
- What are the benefits from addressing the problem, which will help to prioritize sites
 - Improved safety
 - Free up equipment and crews for other locations
- On site visits and discussions with local and regional staff are essential

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Source of Blowing Snow Problem

Is the problem associated with near or far snow or both?

- Amount of snow transported as near snow may be small but can be a dominant cause of icy roads and accidents especially where there are high embankments with no vegetation

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Sources of Problem

- There are a number of potential issues with blowing snow and the solutions will vary
 - Cross cut geometry
 - » Drifts in cuts can encroach on roads
 - » High embankments with steep slopes create problems areas
 - Horizontal alignment
 - » Road alignment parallel to wind direction reduces drifting but may increase visibility and icing problems
 - Vertical alignment
 - » On upgrades with slower truck speeds, berms may be higher and closer to the road
 - Roadside structures, safety barriers and vegetation can cause drifts

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Snow Fence Design

- Snow fences- either structural or living – are only some of the options to address blowing and drifting snow
- The situation needs to be addressed properly so that the best solution is implemented
- Other possible solutions may include
 - Modification of cross sections
 - Changes in snow removal practices
 - Modification of safety barriers
 - Management of roadside vegetation or structures including signs

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Controlling Far Snow with Snow Fences

Keys for a successful installation:

- Adequate storage capacity
 - » Factors such as height, porosity and location are important
- Durable so that it lasts
 - » Benefits associated with initial investment increase over time
- Proper coverage of problem area
 - » Long fences without openings and gaps

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Snow Fence Design

- Several important factors associated with proper design and placement of snow fences
- Calculating snow transport (i.e. the amount of snow transported by the wind over a given period of time and distance) or capacity needed
 - » Identify the snowfall over the snow accumulation season
 - » Identify the snowfall water equivalent
 - » Identify the relocation coefficient
 - » Determine the prevailing direction of greatest snow transport
 - ① Measure orientation of snow drifts formed by large objects late in the snow season
 - ② Analyze historical wind records
 - » Determine the fetch distance for your location

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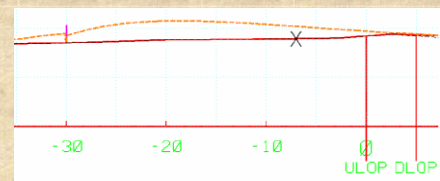
Snow Fence Design

- ◆ Determine required snow fence height
 - Distance from the road
- ◆ Determine required set back for snow fence
 - Key factors are
 - » Amount of transported snow
 - » Porosity of snow fence
 - » Height of snow fence
- ◆ Length fence should extend from either side of the problem area is calculated

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Snow Fence Design - Snowman



- Tool can be used to develop specific parameters for snow fence design based on site specific conditions
- Precise site specific data is required from a survey and weather data bases

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Assessing Site Conditions for Plants



Assessing Site Specific Conditions

- Living snow fence is permanent, compared to temporary snow fence.
- More permanent characteristics of living snow fences offers unique challenges/opportunities in working with landowners
- Landowner objectives
 - Clearly identify and discuss the landowner's short and longer term plans and intentions for the area being considered
 - Design will have to fit with the landowner's plans and preferences for the area
 - » Location of living snow fence may not be ideal
 - » Planting design and species selection may have to be adjusted to accommodate landowner
 - » Site preparation and maintenance may have to be modified

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Landowner Involvement is Essential



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Assessing Site Specific Conditions

- Successful living snow fences start with proper site assessment
- Proper site evaluation will help to avoid many establishment and long term growth and survival problems
 - Site limitations such as wet areas, excessive slopes, stones, fence line removal/trimming
 - Soil conditions
 - Current and previous land use history
 - Existing vegetation
 - » Woody plants
 - » herbaceous annual or perennials
 - » agricultural crop

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Site Limitations

- Walk the site, to see if there are any barriers to preparing, planting or maintaining the site
- If limitations exist, work with landowner and create a plan to modify them if possible
 - Physically modify the site
 - Adapt equipment to suit the site
 - Change the snow fence design to avoid limitations

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Site Assessment – Soil Conditions

- ◆ Soil survey
- ◆ Soil samples and testing
- ◆ Site specific assessments
 - Drainage problems
 - Bulk density or root growth restrictions from hardpans or fill material

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Assessing Site Specific Conditions

- ◆ Soil type and conditions
 - » USDA soil survey information for fields or areas away from the right of way
 - » Specific soil conditions should be assessed, especially on right of ways
 - ◆ Soil samples and testing
 - ◆ Identify other potential limitations such as wet or seasonally flooded areas, rocks, fence lines, other barriers
 - » Collect soil samples, assess rooting depth and potential barriers to successful growth

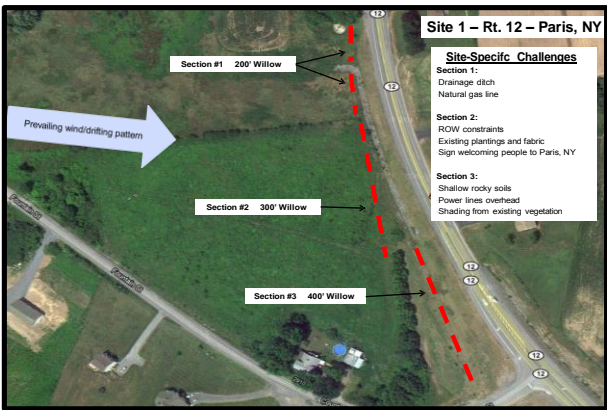
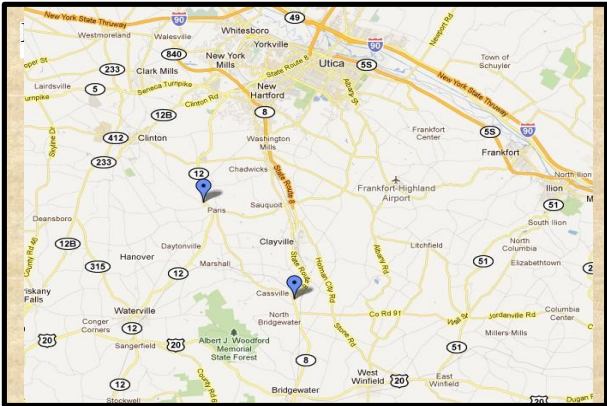
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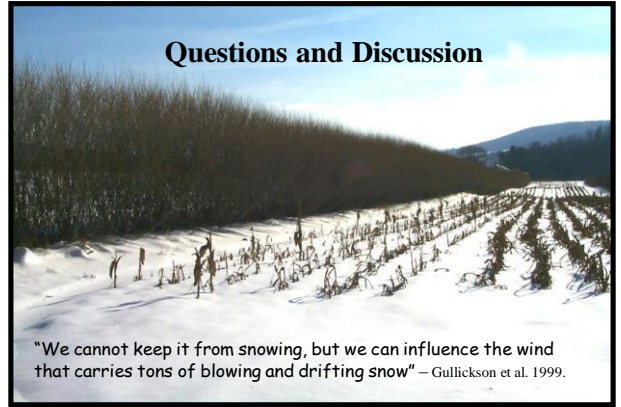
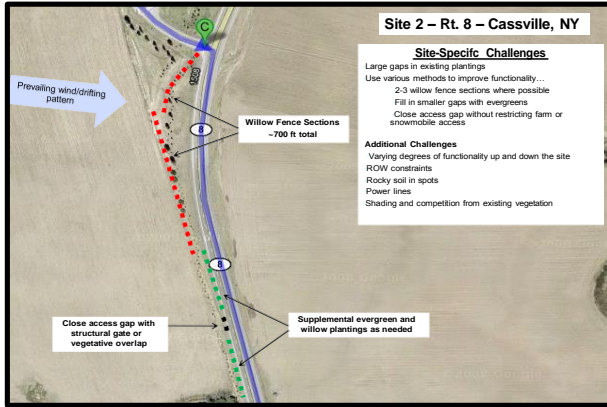
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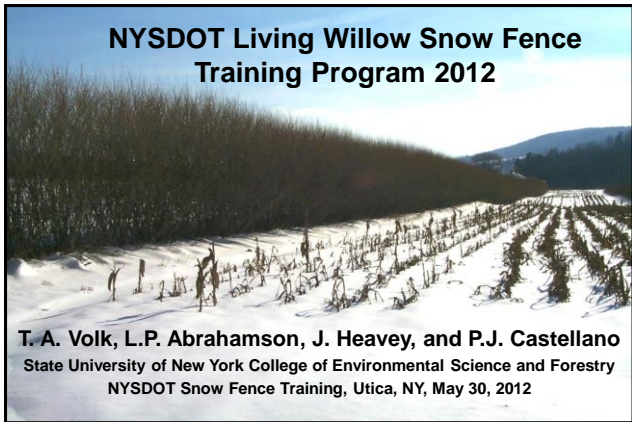
Soil Sampling

- ◆ Make use of Cornell Cooperative Extension sampling protocol and testing lab
- ◆ For woody plants use recommended sampling depths of 0 – 8 inches and 8 – 24 inches

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ESF Fall Class – Principles of Blowing Snow and Living Snow Fence Design

- ◆ Structural and living snow fences
- ◆ Principles of moving snow
- ◆ How snow fences work
- ◆ Snow fence design
- ◆ Site assessment for living snow fences

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ESF Today's Training

- ◆ Selecting plants for living snow fences
- ◆ Installation and maintenance of living snow fences
 - Site preparation
 - Weed control both chemical and mechanical
 - Planting living snow fences
 - Post planting weed control

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ESF Selecting Plants for Living Snow Fences

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ESF Plant Hardiness Zones

Zone	Arg. Annual Low
1	-40° through -50°
2	-30° through -40°
3	-20° through -30°
4	-10° through -20°
5	0° through -10°
6	10° through 0°
7	20° through 10°
8	30° through 20°
9	40° through 30°
10	50° through 40°

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ESF Selecting Plants – Growth Characteristics

- ◆ A limitation of living snow fences is the time required for them to become effective
 - Can take up to 20 years
 - But can be as short as 2 – 3 years
- ◆ Time for living snow fences to become effective depends on:
 - Site preparation prior to planting
 - Growth rate of plants
 - Growth form and habit of plants
 - Spacing of plants
 - Management of site (weeds and nutrients)
 - Quantity of snow transport

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Selecting Plants – Growth Characteristics

- ◆ Growth rate
 - Slower growing plants will take longer to form an effective living snow fence
 - » In some cases this can be 15 – 20 years
 - » Greater potential for damage during this time resulting in gaps
 - Effect of living snow fence will vary as the plants develop, so different growth stages should be considered in the design
 - Interim measures, such as structural snow fences may be required
 - Care in placement is necessary so developing plants do not become buried and damaged by snow drifts
 - Using a mixture of plants with slower and faster growth rates can be effective

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First Year Growth of Shrub Willow Double Row Living Snow Fence

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Willow Living Snow Fence One Year Regrowth on Two Year Old Roots



© The Research



Willow Living Snow Fence Two Year Regrowth on Three Year Old Roots



© The Research Foundation of SUNY



Selecting Plants – Growth Characteristics



This variety of willow (*S. purpurea*) had prostrate growth when planted in a single row living snow fence

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- ◆ Height of the plant where the density is great enough to influence wind speed
 - Effective height of the plant will influence the amount of snow that can be stored
 - Effective height does not necessarily correspond to the general height of the plant



Selecting Plants – Growth Characteristics

- ◆ Plants need to have dense foliage or branching pattern that extends to close to ground level
 - Self pruning species should be avoided
 - Large gaps (> 10 – 15% of snow fence height) at the bottom of the plant can create wind tunnels and exacerbate blowing snow problems

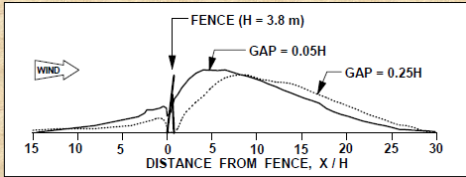
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Selecting Plants – Growth Characteristics

- ◆ A larger space between the ground and the bottom of the snow fence minimizes snow deposition close to the snow fence
- ◆ With strong winds and a solid structural (Wyoming) snow fence, larger gaps creates a longer distribution pattern and less snow accumulation on the windward side
- ◆ Fences that become buried are less efficient at trapping snow

Figure 3.47. Comparison of drifts formed by two 3.8-m (12.4-ft) Wyoming fences that have 30- and 90-cm (12- and 36-in.) bottom gaps, respectively (Tabler 1986).



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Selecting Plants – Growth Characteristics

- ◆ Gaps or openings in living snow fences caused by mortality can result in large drifts downwind
 - Avoid creation of gaps by planting multiple rows and staggering plantings
 - Select plants that are suited to the conditions of the site
 - Gaps that do result should be filled with structural snow fence until replacement vegetation can be established

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Continuous Living Snow Fences

- ◆ Snow fences should be continuous without openings
- ◆ Access fields and rights-of-way around ends of snow fences
- ◆ If access lanes are required, place them at an angle to the prevailing wind

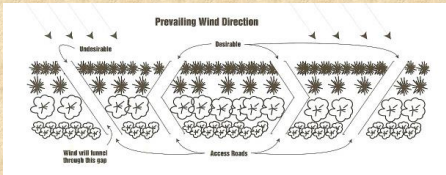


Figure 3.5. Access lanes and roads should be at an angle to prevailing or troublesome winds.

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Selecting Plants – Growth Characteristics



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Open wind speed 20 M.P.H.
Deciduous 25%-35% density

1/2 distance from windward side	5H	10H	15H	20H	30H
Miles per hour	10	13	16	17	20
% of open wind speed	50%	65%	80%	85%	100%

Open wind speed 20 M.P.H.
Conifer 40%-60% density

1/2 distance from windward side	5H	10H	15H	20H	30H
Miles per hour	6	10	12	15	19
% of open wind speed	30%	50%	60%	75%	95%

Open wind speed 20 M.P.H.
Multi-row 60%-80% density

1/2 distance from windward side	5H	10H	15H	20H	30H
Miles per hour	5	7	13	17	19
% of open wind speed	25%	35%	65%	85%	95%

Open wind speed 20 M.P.H.
Solid fence 100% density

1/2 distance from windward side	5H	10H	15H	20H	30H
Miles per hour	5	14	18	19	20
% of open wind speed	25%	70%	90%	95%	100%

(PNW 2003)

Figure 3.1. Windbreak density influences the leeward wind protection zone.

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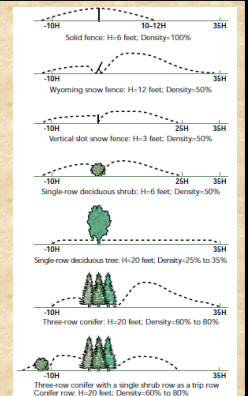
Optical Density

- ◆ Optical Density
 - The amount of area composed of solid material (porosity is the amount of open area that is **not** covered in solid material)
 - For deciduous woody plants this is all stem and branch material
 - For conifers this includes foliage
 - Solid barrier is 100% density (0% porosity)
- ◆ Vary density by species selection, spacing, management, number of rows
- ◆ Living snow fences with high density >65% will generally have narrower drift patterns



Effect of Density and Height

- ◆ Density and height of snow fences influence the storage capacity and drift size and shape
- ◆ Can vary this feature with species selection, number of rows, spacing and other management decisions



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Selecting Plants – Plant Characteristics Change Over Time

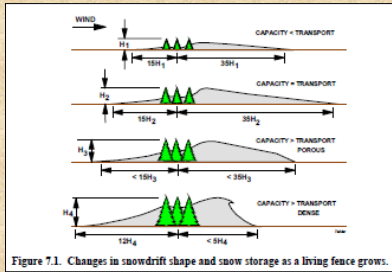


Figure 1.1. Changes in snowdrift shape and snow storage as a living fence grows.

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(Tabler 2003)



One Year Old Coppice Growth on a Two Year Old Root System – Single Row



Fish Creek - Density - 47.5%



SV1 - Density - 23.7%

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Two Year Old Coppice Growth on a Three Year Old Root System – Single Row



Fish Creek - Density - 50%

SV1 - Density - 53%

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Snow Break Forests

- ◆ Dense plantings that act as a solid barrier can be planted closer to the road
- ◆ Shade from plants may effect road conditions
- ◆ Drifts may occur as plants are developing

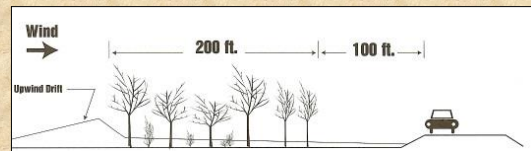


Figure 3.24. Snow break forests used in Japan utilize the principle that dense plantings act as solid barriers to induce snow deposition on the upwind side. (Tabler 1994, p. 282)

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Selecting Plants – Growth Characteristics

- ◆ Ability to withstand wind
- ◆ Ability to withstand snow loads
- ◆ Native or non native
- ◆ Invasive
- ◆ Species longevity
- ◆ Salt tolerance
- ◆ Avoid plants for which a major pest or disease problem is known
 - Elms or hybrid poplar in our region
- ◆ Canopy width to facilitate maintenance and avoid problems with utilities

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Beneficial Willow Characteristics



20 inch willow cutting planted in a living snow fence

- ◆ Easy to establish with unrooted cuttings
 - Easier to handle
 - More tolerant of delays in the field
 - Cheaper than rooted stock
- ◆ Tolerates planting at high density (1.5 – 2 ft spacing)

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Beneficial Willow Characteristics



Measuring optical density on a living willow snow fence in Cortland County, NY

- ◆ Rapid height growth
 - Can reach >20 ft in 3-years
 - Can reach 50% density in 3 years
- ◆ Larger planting stock can be used to accelerate establishment
- ◆ Effective in as little as two to three years

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Beneficial Willow Characteristics



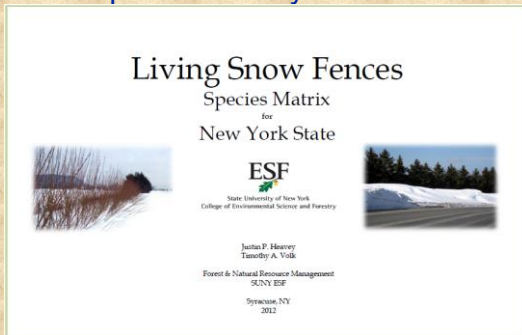
Willow (*S. purpurea*) living snow fence five months after coppicing

- ◆ Coppicing ability creates good density from the ground to top of the crown
 - Mature willow snow fence has a measured density of 60-70%
- ◆ Once established, maintenance is minimal
- ◆ Height and density can be modified by selecting willow varieties and changing spacing and/or management

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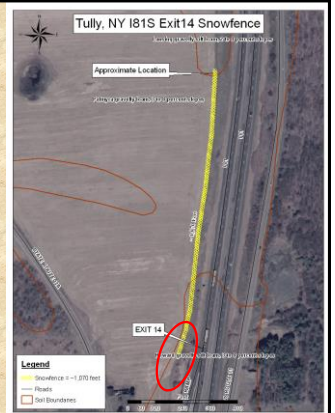
Species/Variety Selection



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Site Characteristics Influence Plant Selection



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Selecting Plants



March 2010



This variety of willow was damaged during the first winter by snow drifts that formed due to topographic features at this site.

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Selecting Plants



First year willow clone breaking under snow load at 81S site near Tully



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Route 81S Near Tully, NY



➤ Concern about snow drift forming around the end of the living snow fence

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Installation and Maintenance of Living Snow Fences

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Successful Living Snow Fence Installation

- ◆ Keys for successful installation of living snow fences
 - Proper site preparation based on good site assessment
 - Careful installation of plants
 - Control of grass and broadleaf weeds for 2-3 years after planting

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Site Preparation

- ◆ Site preparation is a one time investment that influences the effectiveness of the living snow fence for years or decades
 - Take the time, make the effort, do it correctly!
- ◆ An important rule for successful living snow fence establishment is to address weed problems and soil limitations during site preparation BEFORE the living snow fence is planted
- ◆ Controlling weeds or modifying site conditions after planting is more costly and time consuming!

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Site Preparation

- ◆ Benefits of proper site preparation
 - Control of existing weed pressure
 - Initial control of future weed pressure to minimize future maintenance costs and damage to plants in the living snow fence
 - Improve soil structure in rooting zone
 - Expand soil volume for rooting
- ◆ Results
 - More effective establishment
 - Reduced maintenance efforts and costs
 - Increased growth rate resulting in shorter time for living snow fence to be effective

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Weed Control

- ◆ Weeds compete for moisture, nutrients and light
- ◆ Maintain a weed free area 2-3 ft away from where plants are placed
- ◆ Control weeds for 2-3 year establishment period

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Site Preparation Flow Chart

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Site Preparation - Mechanical

- ◆ Cultivation to reduce competition of existing grasses and prepare the soil for planting
 - Subsoiling, disking, rototiller
 - Will not provide long term control of perennial vegetation
- ◆ Disturbs the soil
 - Increase soil permeability and aeration
 - Reduce or remove barriers limiting plant growth
 - Increases soil volume for roots to acquire nutrients and water

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Mechanical Site Preparation



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Site Preparation - Mechanical



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Site Preparation - Chemical

- ◆ Herbicides to control competing vegetation before planting
 - If possible this is best done in the late summer or early fall prior to planting
 - Chemical control of existing perennial vegetation is not as effective in the spring
 - Limitations and restrictions on herbicide use
 - Follow label guidelines

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Site Preparation - Chemical



One-year old willow snow fence with weed & deer browse problems in western NY



Establishing a living snow fence in Cortland County in the spring of 2001.

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- ◆ Good weed control for the first two years
 - Herbicides for Site Prep fall before planting
 - » glyphosate (Round Up - Touchdown) 2 lbs. a.i./Acre
 - Depending on weeds present may also add following in a herbicide mixture:
 - » 2,4-D @ .5 - 1 lb a.i./Acre
 - » dicamba (Banvel) @ .5 - 1 lb a.i./Acre
 - » Mixture of 2,4-D and triclopyr (Crossbow) (.5 - 1 lb a.i./A and ¼ - ½ lb a.i./A)
 - Herbicides for Site Prep in spring of planting
 - » glyphosate (Round Up - Touchdown) 2 lbs. a.i./Acre



Existing Vegetation – Woody Plants

- ◆ Bush hog then apply appropriate herbicide
- ◆ Stumps less than 3" can usually be removed during tillage operations
- ◆ Stumps >3"
 - Remove if only a few
 - Incorporate plants into the living snow fence

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Existing Vegetation – Herbaceous

- ◆ Bush hog if greater than 10-12 inches tall because effectiveness of herbicide will be limited
- ◆ Determine type of vegetation
 - Perennial – herbicide and mechanical cultivation
 - » Check efficacy of post emergent herbicides after use by inspecting above and below ground plant parts
 - » Retreat sections that were missed or where herbicide was not effective
 - Annual – mechanical cultivation alone may be effective

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Existing Vegetation – Agricultural Crop

- ◆ If actively used for cropping then ask for list and rates of recent herbicides used
- ◆ Some herbicides have a carry over effect and can influence establishment of new plants
- ◆ Annual crop – mechanical tillage
- ◆ Perennial crop – chemical and mechanical control

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Post Planting Weed Control

- ◆ No method provides 100% guarantee
- ◆ Periodic monitoring of site is necessary
- ◆ Be prepared to respond quickly to weed pressure before it becomes a serious issue
 - i.e. smaller weeds are easier to control and will have less effect on the plants you are trying to establish

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Post Planting Weed Control – Mechanical

- ◆ Mechanical cultivation
 - Various types of equipment are available
 - » Disks
 - » Spring tooth harrows
 - » Cultivators
 - » Specialized cultivators
 - Work best on young weed seedlings that are not well established
 - Less aggressive cultivation will not be effective on perennial weeds

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Post Planting Weed Control – Mechanical

- ◆ Mowing of adjacent weeds
 - Important for areas beyond immediate 2-3 foot zone around living snow fence plants
 - Will not effectively reduce weed competition for water and nutrients in the immediate zone around establishing plants

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Post Planting Weed Control - Mechanical

- ◆ Mechanical cultivation alone not recommended
 - Timing is essential and hard to ensure
 - Up to 4 – 5 cultivations per year required for effective control
 - With each cultivation there is potential for damage to living snow fence plants
 - Difficult to mechanically control weeds near and in between plants
 - » Often requires manual weed control to be effective

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Post Planting Weed Control - Chemical

- ◆ Can be effective in combination with proper site preparation
- ◆ Requires proper selection and use of herbicide
- ◆ Monitoring still required to ensure that weed control goals are being met

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Post Planting Weed Control - Preemergence



One-year old willow snow fence with weed & deer browse problems in NY



Establishing a living snow fence in Cortland County in the spring of 2001.
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- ◆ Proper follow up weed control after planting is essential for success
 - Pre-emergence herbicides:
 - » oxyfluorfen (Goal)
 - ◆ 1 – 2 lbs a.i./Acre
 - » simazine (not in sandy soils)
 - ◆ 2 – 4 lbs a.i./Acre
 - » pendimethalin (Prowl – Pendulum)
 - ◆ 2 lbs a.i./Acre
 - Other pre-emergence herbicides that look ok
 - » norflurazon (Solicam) (.8lb a.i./A)
 - » flumioxazin (Sureguard) (.25lb a.i./A)
 - » imazaquin (Scepter) (.125lb a.i./A)



Post Planting Weed Control – Post Emergence



One-year old willow snow fence with weed & deer browse problems in NY



Establishing a living snow fence in Cortland County in the spring of 2001.
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- ◆ Proper follow up weed control after planting is essential for success
 - Post-emergence herbicides:
 - » glyphosate (Round Up - Touchdown)
 - ◆ 1- 2 lbs. a.i./Acre shielded/directed spray
 - » paraquat (Gramoxone) (burn down only)
 - ◆ 5 - 1 lbs. a.i./Acre shielded/directed spray
 - » clopyralid (Stinger) (not in Nassau & Suffolk Counties – max of .25 lb a.i./A/year in NY)
 - ◆ .125 - .25 lb a.i./Acre
 - » Any grass only herbicide
 - ◆ Fusilade or Poast, etc.



Post Planting Weed Control – Organic Mulches

- ◆ Can help with weed control but will need to be maintained over time if it is the primary weed control method
 - Annual addition of mulch as material degrades and weeds become established on the surface
- ◆ Additional benefits include
 - Moisture retention
 - Moderated soil temperatures which can potentially extend root growth into the fall but slows soil warming in the spring

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Post Planting Weed Control – Organic Mulches

- ◆ Wood chips are the preferred mulch
 - 3 – 4 inch layer of chips
 - If possible the lower layer should be composted
- ◆ Limitations
 - Potential for introduction of additional weed seeds
 - May enhance rodent damage in the winter
 - Labor cost associated with spreading mulch

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Post Planting Weed Control – Landscape Fabric



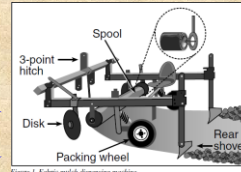
Establishing a willow living snow fence in Lewis Co., NY in the spring of 1999.

- ◆ Can be effective for 1 – 6 years or more depending on type of fabric and use
- ◆ Mats or rolls available
- ◆ Select material that has a projected lifespan of 3 – 5 years
 - Breakdown will be slower if not exposed to sunlight
- ◆ Recommended width is 6 ft, but comes in 3 – 6+ ft widths

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Fabric Barrier



(NSU 2004)

Fabric Advantages

- ◆ Applied only once
- ◆ Improved tree and shrub establishment and survival
- ◆ Increases growth rates immediately following planting
- ◆ Easier and more timely weed control
- ◆ Long lasting weed control
- ◆ Comparable cost to other weed control methods averaged over several years

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Fabric Barrier



(PMO 2003)

- ◆ **Fabric Disadvantages**
 - Initially expensive
 - Requires specialized machinery to install or done by hand
 - Proper installation is critical to prevent pulling loose in winds
 - Does not break down, especially within the shade of plants or under mulch
 - Stems may be girdled by fabric as trees and shrubs grow
 - Dense sod can become established on top of fabric, negating benefits and complicating future maintenance
 - Ideal habitat for ground hogs, voles and mice

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Post Planting Weed Control – Landscape Fabric

- ◆ Should remove or till in weeds before use
- ◆ Fabric needs to be secured at time of installation to avoid abrasion of planted material
 - Plastic pegs, cover edges with soil (but will promote weed growth), cover with mulch
- ◆ Create openings in fabric using X-shaped cuts to avoid girdling as plants grow

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Post Planting Weed Control – Landscape Fabric

- ◆ Improper installation can result in significant damage to plants
 - Broken stems and braches
 - Girdling from abrasion
 - Plants covered and smothered
 - Excessive temperatures under the fabric

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Post Planting Weed Control – Landscape Fabric

- ◆ Can be very effective and beneficial
- ◆ BUT
 - When installed improperly it can cause extensive damage




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Fabric Barrier Recommendations

Fabric Management

- ◆ Inspect as part of monitoring in first 1 – 2 years
- ◆ Ensure edges are firmly anchored
- ◆ Ensure openings are large enough to avoid stem damage
- ◆ Control aggressive weeds that may establish in fabric openings
- ◆ Enlarge openings as needed to prevent stem girdling
- ◆ Cover with mulch but leave area immediately around plants uncovered



Large X shaped openings in the fabric are important for the long term success of the living snow fence

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Mulch



- ◆ Try to use wood chips that have been stored for a short period of time and are not mixed with soil
- ◆ Decomposed wood chips or some sources of mulch have the potential to introduce new weeds onto the site

Thistles growing in area mulched with wood chips but not elsewhere. Probably introduced in wood chips.

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Paper Barrier Recommendations

- ◆ Use paper or biodegradable fabric that will break down in 1-3 years
- ◆ Needs to be strong enough to provide at least one year of effective weed control
- ◆ Avoids problems associated with girdling and root development
- ◆ Easy to plant through
- ◆ Currently more costly than traditional landscape fabric, but options being pursued

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Paper or Biodegradable Weed Barrier



© The Research Foundation of SUNY



Planting Stock

- ◆ Rooted planted stock or unrooted cuttings

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Planting Rooted Stock

- ◆ Different types available
 - Bare root or plug
- ◆ Small sized material is lower cost and easier to handle and plant
- ◆ Available from commercial nurseries or from DEC or Soil and Water Conservation Districts

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Planting Rooted Stock



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Planting Rooted Stock

- ◆ Proper care of rooted stock is essential
 - Keep plants moist and in a cool location
 - Roots must never dry out!
- ◆ Make the hole deep enough for all roots.
- ◆ Cut long roots back to 10 or 12 inches.
- ◆ Remove one tree at a time from bucket only after hole is ready for the tree.
- ◆ Keep foreign matter (leaves, sticks, rocks, and dry soil) out of hole.
- ◆ Place all tree roots in a downward position.
- ◆ Place tree in center of hole.
- ◆ Hold treetop upright while working soil around roots.

(adapted from PNW 2003)

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Planting Rooted Stock

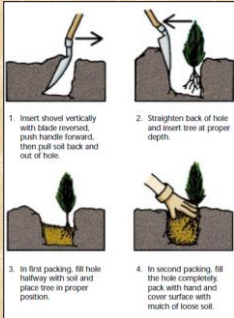
- ◆ Firm soil around roots by hand while filling hole, leaving no air spaces. Make sure to use moist soil.
- ◆ Bring soil level to root collar (look for color change on stem) above the first roots. Too deep is better than too shallow.
- ◆ Firm soil all around tree by hand to give good compaction.

(adapted from PNW 2003)

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Planting Rooted Stock



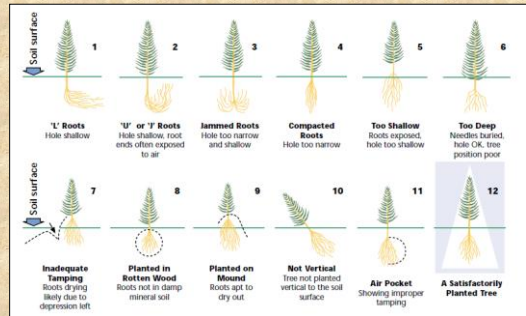
- ◆ Trees and shrubs planted improperly have little chance to survive. Take an extra moment with each plant and make sure they are planted properly

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(adapted from PNW 2003)



Proper Planting is Essential



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(PNW 2003)



Planting – Unrooted Cuttings

- ◆ Used for establishing willow and hybrid poplar
- ◆ Lower cost and easier to handle
- ◆ Quality of material is important
- ◆ Recommend 10 – 20” cuttings
- ◆ Keep frozen until just before planting
- ◆ Store in cool location and do not allow them to dry out after being delivered
- ◆ Plant with buds pointing up with at least one bud above ground

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Planting – Unrooted Cuttings



Planting of unrooted hardwood cuttings is easy and relatively quick

- ◆ Plant 10 to 20 in. long cuttings between late April and early June
- ◆ Use high quality planting stock that has been properly stored and cared for

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Post Planting Care



Weed control is probably the single largest factor for the failure of living snow fences

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- ◆ Regular monitoring is needed to quickly identify problems before they become serious issues
 - Weed pressure
 - Browsing damage
 - Pest and disease problems
 - Herbicide damage from improper use or drift
 - Other factors that may be limiting growth



Post Planting Care

- ◆ Weed control will be necessary for 2-3 seasons at least
 - Longer for sites where growth of shrubs or trees is slow
- ◆ Replanting
 - Even under the best conditions some plants will not survive
 - Gaps will create additional problems in the future
- ◆ Browsing control
 - At some locations deer browsing pressure can severely limit growth of plants
 - Recommend the use of deer repellent early to discourage deer from developing browsing habit

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Post Planting Care

- ◆ Coppicing
 - For willows coppicing after the first year of growth is recommended to promote the development of multiple stems
- ◆ Fertilizer may be applied after the plants are established
 - Fertilizer on young or poorly established plants will just feed the weeds
 - Spring application of fertilizer based on soil analysis or plant tissue analysis

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Successful Installations



Willow snow fence three months after planting.



First year of growth after coppicing

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Successful Installations



Willow snow fence two months after planting

© The Research Foundation of SUNY



Route 81S Near Tully, NY



- >Planted May 2009
- >Excellent initial survival
- >Late July 2009

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Route 81S Near Tully, NY



August 2009

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Route 81S Near Tully, NY



March 2010

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Route 81S Near Tully, NY

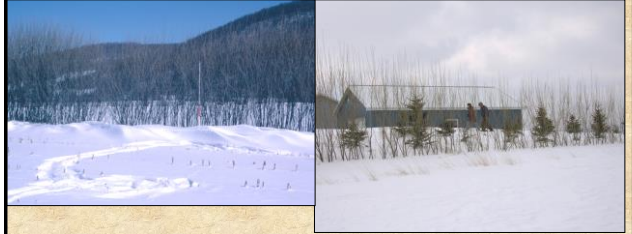
March 2010



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Successful Installations



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Successful Installations



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Lessons Learned/Shared Experiences

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Field Installation Activities

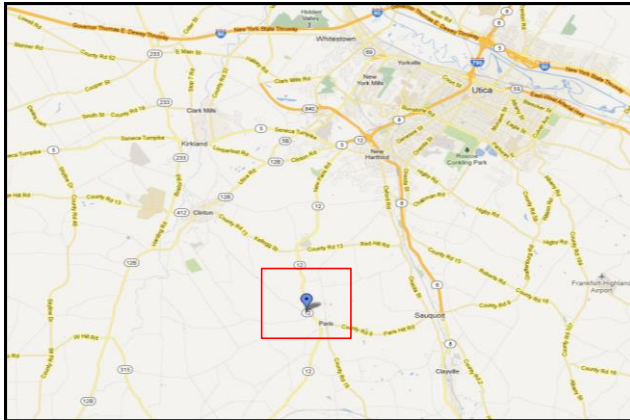
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Willow Snow Fence Installation Rt. 12 - Paris NY, May, 2012



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ESF Site Limitations and Challenges

- Overhead power lines. 20' clearance requirement on either side (at maturity)
- Tree line creates shading and limited planting space
- Existing living snow fence situated on ROW boundary. Removal of old fence or land owner consent required for new fence
- High percentage of fill. Large chunks of concrete & blacktop
- Second land owner consent required for planting & tractor access
- Shallow, stony soils
- Paris town sign. Maintain unobstructed LOS
- Two natural gas pipelines. Required 25' clearance requirement on either side
- Gap in fence created by culvert

Site Challenges & Obstructions

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ESF Working with Site Conditions

- Tree line (shade)
- Existing snow fences
- Utilities (electric & gas)
- Rocky soils & fill
- Paris town sign
- Ditches, etc.

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ESF Living Snow Fence Design

Rt. 12 - Paris, NY Willow Living Snow Fence

Section #1 525' Willow LSF

Section #2 70' Willow LSF

Section #3 525' Willow LSF

Section #4 70' Willow LSF

Section #5 70' Willow LSF

Total Length: 860' Willow LSF

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ESF Site Preparation

- Sprayed site to kill existing vegetation
- Subsoiled site due to concerns about restrictive layers
 - One section with concrete and asphalt fill created additional site preparation problems
- Amended soil in one section
- Rototilled site and laid paper landscape fabric

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Site Preparation – Rip soil



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Site Preparation – Rototill



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Site Preparation – Add Soil Amendments



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Site Preparation – Lay Paper Fabric



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Site Preparation – Secure Fabric



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Site Preparation

- ◆ Mark landscape fabric for planting with willow cuttings
 - 2.5 ft between double rows
 - 2 ft along the rows in a staggered design
 - Result is a plant about every foot
 - Plant directly through paper material

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Planting

- ◆ Plant 20 inch long cuttings for most of the site
- ◆ Add mulch and spread to a depth of 2-3 inches
 - Be sure to cover or secure the fabric so it does not get picked up by the wind

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Follow Up Monitoring and Maintenance



Weed pressure beginning to build at a new living snow fence

- ◆ Important to regularly monitor new plantings for weeds, deer browsing, other problems
- ◆ Early action to correct problems is much easier than trying to address it later

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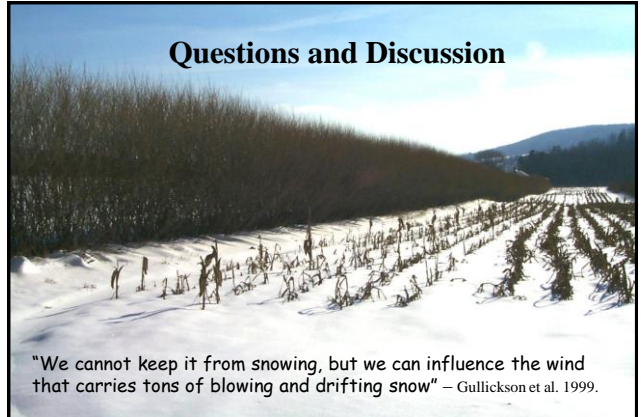


Site Preparation and Installation Summary

- ◆ Decisions early in the design and installation process have a long term effect
- ◆ Select the plants most suited for the site conditions and goal of the living snow fence
- ◆ Proper site preparation is essential and will provide benefits for years in the future
- ◆ Weeds are the largest challenge but can be managed using a variety of techniques

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Questions and Discussion



"We cannot keep it from snowing, but we can influence the wind that carries tons of blowing and drifting snow" – Gullickson et al. 1999.

Living Snow Fence Design and Installation Course Instructor's Notes

Overview

Congratulations! You will be participating in training for New York State Department of Transportation (NYSDOT) staff in the design and installation of living snow fence.

The challenge and opportunity in this training is that it includes many different concepts and competencies. The knowledge to be shared ranges from calculating snow accumulations, to actually planting vegetation that will hold back snow.

While you may not be familiar with every element in the living snow fence design and installation process, this document and the accompanying presentations will enable you to develop an effective class. As an added benefit, once the class is complete, a Residency will have a completed living snow fence in the ground. If the planting is done correctly, the installation will could begin trapping blowing snow the second or third winter after planting, depending on the species chosen and the size of the planting stock at installation.

Background

Along New York State highways, snow and ice control is sometimes more difficult because winds blow snow off adjoining property and onto highway. Blowing and drifting snow requires frequent plowing or applications of de-icing chemicals. Blowing and drifting snow can also create safety problems by decreasing driver visibility. In severe storms, or storms where the New York State Department of Transportation (NYSDOT) plowing forces are depleted, snow can cover a road faster than it can be removed. This could result in impaired or dangerous driving conditions.

Snow and ice control consultants have discovered roadside design and permanent or temporary engineered snow fences, from manmade materials, can provide relief from blowing snow. However, road design cannot solve every problem. In some NYSDOT Regions, temporary snow fences are installed and removed seasonally, which is time consuming and labor-intensive. A four feet high temporary snow fence, a standard height, is often not effective in some settings; raising such fences to six feet heights may not work if the materials are not strong enough. A permanent snow fence eliminates the need for installation in the fall and removal in the spring. However, it can be costly; it may not be popular with landowners; and it may affect land uses such as agriculture or athletic fields.

In response to these issues, transportation agencies are re-examining the potential of vegetation to control blowing and drifting snow on highways. These efforts have been inspired by a practice, popularized during the Depression, of planting trees and shrubs to reduce erosion or trap snow. The terms for this practice were “windbreaks,” “shelterbelts” or “snow breaks.”

This class takes best practices from NYSDOT and other transportation agencies in the United States and Canada, along with research from SUNY-ESF, so that a Region or Residency can design and install living snow fences to improve winter mobility/safety and reduce the cost of snow and ice control

Class information

This guide and the accompanying materials were prepared by researchers from the State University of New York College of Environmental Science and Forestry (SUNY-ESF), with assistance from NYSDOT

staff who are experienced in designing and installing living snow fence.

All items in this package have been tested in four sets of classes offered between 2009 and 2011.

A “class” will have two sessions, lasting about a day and a half.

- Session 1 is a day long site assessment and design session, that starts at 8:30 am and goes to 4 or 4:30 pm.
- Session 2 is an installation session in the field that lasts half to three quarters of a day, starting between 7:30 am and 8 am and goes to noon.

As with any class with fieldwork, you may modify the schedule to accommodate weather changes.

For Session 1, the assessment and design session, you will need a classroom and access to the proposed installation site. About three quarters of Session 1 occurs in the classroom. A trip to the installation site composes the rest of the class.

For Session 2, the installation session, you will have some overview information that can be provided in the classroom or at an assembly point. However, most of Session 2 will occur at the installation site in the field.

The maximum class size is recommended to be 25 people. The limiting factor on class size is Session 2. Because of safety on the right of way, having more than 25 people working on the installation makes safety and work zone traffic control more difficult. If your location’s training needs require, you can have more than 25 people in Session 1. However, not all these people would be able to fit in Session 2.

Choosing a Site

Based on past experience, here are some factors that you should consider in selecting a site for Sessions 1 and 2:

- The installation location must have a pressing transportation safety/operational need related to blowing/drifted snow.
- The site for Session 1 must be able to support a one day instructional experience. Some of the details are listed in the following section.
- The site for Session 2 must have
 - Enough property, either with State owned right of way or with a landowner willing to allow planting on his or her property, to install a snow fence with enough room that snow will not pile up in the highway lanes.
 - Adequate right of way access and space for transporting 25 people - - in multi-occupancy or single occupancy vehicles - - without compromising student safety.

Regional/Residency Support Needed

For this class to work, a Region or Residency must provide the following:

- Vegetation to install in Session 2. Before starting the class, the Instructor is encouraged to develop a list of possible vegetation types and to discuss whether the Region or Residency can fund the purchase of the vegetation.

- A landowner release if the installation will be located off the right of way. A sample is attached.
- A site for Session 1 that has
 - Adequate space for 30 people.
 - Adequate electrical service for up to five personal computers to operate SnoMan, a computer design program for blowing and drifting snow, and for a projector.
 - Accommodations to provide a lunch. Students would either bring their own lunch or a group of students would fund and order a meal for delivery.
- Regional/residency support for site prep/installation. This "support" would include:
 - Site preparation, such as clearance of site vegetation by herbicides or other means, and ripping/tilling of soil at snow fence site.
 - Provision of clean wood chips to mulch completed planting. A tractor with tilling and ripping attachments is needed for site prep and can also move chips if it has a bucket. A loader or Bob Cat is strongly suggested to simplify moving the chips.
 - Assistance with safety during installation, including providing a safety briefing and design/set up work zone traffic control.
 - On site support during installation, including, providing water for students, delivery and movement of materials, and installation assistance at class and afterwards. Depending on the design, the entire installation could be completed during Session 2 or the Residency staff might have to return on a following day to finish planting. Several days of site visits and site preparation is also required prior to the class to prepare the planting strip, stage materials, complete different sections of the fence to various degrees and complete other tasks associated with the “ready-to-go” field training session that occurs within a small window of time relative to the total time required to completely install a LSF.

Sample Agendas

On the following pages are sample agendas. The first could be adapted when you plan to offer Sessions 1 and 2 on consecutive days. The second could be used when Sessions 1 and 2 are separated by weeks, months or a season.

Outline for Living Snow Fence Training
Wednesday May 27, 2009 and Thursday May 28, 2009 in Tully, NY

Note: This schedule may vary, based on weather conditions. If Wednesday is forecast to have better weather than Thursday, the installation segment of the class will occur on Wednesday and Thursday will have a classroom session.

On both days, students should meet at the classroom at Heiberg Memorial Forest (directions attached)

Wednesday May 27, 2009

8:30 Introductions and Welcome

9:00 Principles of Blowing and Drifting Snow

- when snow moves
- how much snow moves

Site Factors Influencing Snow Movement

- effect of slope on snow movement and storage

Characteristics of Living Snow Fences

- factors determining the effectiveness of living snow fences
- snow drift development behind snow fences
- estimated set backs for living snow fences

10:15 Break

10:30 Assessing Site Conditions for Plants

- what plants need to be successful
- soil assessment and testing
- weed assessment and control plan

Selecting Plants for Living Snow Fences

- shrub willow characteristics
- lessons learned

Installation and Maintenance of Living Snow Fences

- success starts with proper site preparation
 - modifying site conditions
- weeds as one of the key factors limiting the success of living snow fences
- tools for effective weed control
- planting willow cuttings
- coppicing and associated benefits

12:00 to 1:00 PM Lunch

1:00 to 1:30 PM? Installation and Maintenance of Living Snow Fences (cont'd)

- success starts with proper site preparation
 - modifying site conditions

- weeds as one of the key factors limiting the success of living snow fences
- tools for effective weed control
- planting willow cuttings
- coppicing and associated benefits

1:30 PM to 2:00 PM? Lessons Learned/Shared Experiences

- sharing from previous experiences with willow and other living snow fence programs will be shared so common errors can be avoided.

2:00 to 4:00 PM Field Tour

- visit existing willow living snow fence on 81 south near Preble.
- background including site preparation and planting
- maintenance operations
- lessons learned

4 to 4:30 P.M. Wrap up and class ends

Thursday May 28, 2009

8:30 AM to ? Overview of Living and Structural Snow Fence Site on 81 North of Tully

? to 12:00 PM: Field Installation of living snow fence along highway 81 north of Tully

- site preparation steps
- planting material care and maintenance
- installation of section of living snow fence

Sample Agendas for Sessions that do not immediately follow each other

Class SYLLABUS

**New York State Department of Transportation (NYSDOT) and
College of Environmental Science and Forestry, State University of New York**

**Region 2 Living Snow Fence Design and Installation Class
Design Session: Thursday October 20, 2011**

**Classroom at the Region 2 Regional Crews Building
2436 Chenango Road, Utica, New York 13502
8:00 AM to 2:30 PM**

- 8 to 8:30 A.M:** **Arrival and sign-in**
- 8:30 A.M.** **Welcome, Introductions and Overview of Design Training:**
Region 2 representative, John Rowen and Tim Volk, SUNY College of
Environmental Forestry
- 9 A.M.** **Background: Tim Volk**
- Principles of Blowing and Drifting Snow and Effect of Snow
Fences
- 10:15 A.M.** **Break**
- 10:30 A.M.** **Snow fence design concepts: Tim Volk**
- 11 A.M.** **Snowman: Computer aided snow fence design: Darrell Kaminski (?)**
- 12:00 P.M.** **Lunch (on your own):**
Possible luncheon choices in Utica/New Hartford include . . .
- 1:00 P.M.** **Wrap up of classroom information**
- 1:30 P.M.** **Visit Routes 12 sites**
- Route 12, between Fountain St. and Shanley Rd.
- **Objective:** continuous willow snow fence up to 900 feet, including corner wrap-around.
 - **Challenges:** narrow ROW, existing vegetation, working with land owner in regards to herbicides and cultivation practices.

**New York State Department of Transportation (NYSDOT) and
College of Environmental Science and Forestry, State University of New York
Region 2 Living Snow Fence Design and Installation Class
Installation Session**

Wednesday May 30, 2012

**Classroom at the Region 2 Regional Crews Building
2436 Chenango Road, Utica, New York 13502 and
Route 12 near Paris in Oneida County**

8:30 AM to 2:30 PM

- 8 A.M.** **Arrival and sign-in**
- 8:30 A.M.** **Installation Session Overview:**
Region 2 rep and Tim Volk, SUNY College of Environmental Forestry
- 8:45 A. M.** **Review of design Principles and Assessing Site Conditions for Plants**
- What plants need to successfully establish
 - Soil assessment and testing
 - Weed assessment and control plan
- Selecting Plants for Living Snow Fences**
- Shrub willow characteristics
 - Lessons learned
- 10:00 A.M.** **Break**
- 10:15 A. M.** **Installation and Maintenance of Living Snow Fences**
- Success starts with proper site preparation
 - Modifying site conditions
 - Weeds as key factor limiting planting success/Effective weed control tools
 - Planting willow cuttings
 - Coppicing and associated benefits
- 11:15 A. M.** **Preparation for Field Session**
- Provide directions to field installation after lunch
 - Safety briefing for field installation
- 11:30 A. M.** **Lunch (on your own)**
- 12:30 P. M.** **Field Installation of living snow fence: Route 12, Paris**
- 2:30 P.M.** **Class conclusion and evaluation**

Presentations

SUNY ESF prepared a presentation on designing and installing a living snow fence. The presentation includes the information for both Sessions 1 and 2.

The presentations are in a PowerPoint format. They include speakers' notes. If you have questions about any of the slides or the notes, please contact [?]

Feel free to customize this presentation so that it fits your schedule. If you have site-specific information, you are encouraged to include that throughout the presentation.

The presentation does not include detailed information on Snowman, which is NYSDOT design software that can help site the living snow fence.

Siting is a key task with living snow fence.

- The vegetation must be planted a sufficient distance from the highway so that it will not result in snow being dumped on the highway.
- Vegetation should also be located so that snow cannot be transported around the edges of the snow fence.



NEW YORK STATE DEPARTMENT OF TRANSPORTATION
Permission to Plant Trees and Shrubs

Property owner(s) name: _____

State Highway # _____

County _____

The undersigned owner of private lands located on the _____ side of the highway

at reference maker _____ and being further identified as

hereby grants permission and gives consent to the Commissioner of Transportation the State of New York, His agents or contractors, to plant trees and shrubs on (my) (our) premises for living snow fences in order to reduce snow drifting across the highway and improve safe operating of motor vehicle for a period of five years. It is anticipated additional snow will accumulate on the premises.

(I) (We) further agree the Department of Transportation of the State of New York may enter (my) (our) premises, through said Department's agents or contractors to perform normal maintenance as required following a five year period after planting and that (I) (We) will obtain written permission from said Department before causing said trees or shrubs to be removed within the five year time period.

Dated _____

In the presence of: _____

Task 2-B: Training Workshops for Living Snow Fence Design, Installation and Maintenance

Task 2-B: Training for LSF Design, Installation and Maintenance

Training materials, including a series of seven fact sheets and two PowerPoint presentations, were prepared to assist in design and installation classes. Training materials were created from an extensive literature review of LSF, previous research and development efforts conducted by SUNY-ESF, and improved methods and protocols developed in this project. Five classes were held during the project. The first four classes were held at four different NYSDOT residencies in Onondaga, Erie, Delaware and Oneida Counties. Each class had two sessions.

In the first session, generally held in the fall, participants learned about basics of blowing snow problems, addressing problems with LSF, site assessment and fence design. In the field component of the fall session, students visited a site identified by residency staff as having a blowing snow problem and addressing the factors for site assessment as a group, including talking through potential challenges to fence installation and possible solutions.

The following spring, the class reconvened for a one- or two-day long session. The classroom aspect of the spring session covered LSF design, installation, maintenance and best practices. In the field component of the session, participants observed and assisted in site preparation and installation of a living snow fence on the site. Shrub willow LSF were used in the field sessions, as this vegetation type is recognized as a best practice for LSF due to the rapid growth rate of willow, the ease of propagation from dormant stem cuttings, tolerance of high planting density, consistent porosity, etc. Protocols to assess and measure LSF sites were developed and applied at each site and these methods and findings were presented and applied in each of the classes as part of the comprehensive demonstrations of site identification, analysis, design, installation and maintenance of LSF. Methods of site assessment included using geographic information systems (GIS) to assess and measure the site, soil sampling and interpretation of results, assessing vegetation and land use history, assessing the blowing snow problem, developing strategies to overcome site challenges (ditches, trees, utilities), etc.

The fifth and final class was planned to be a winter workshop to observe and discuss functional LSF in the landscape. Scheduling of this tour, so participants from multiple residencies across the state could participate, proved difficult amongst competing and uncertain demands on NYSDOT staff for snow and ice control during the winter. A summer class to observe mature LSF was held instead to accommodate previous participants from various residences attending. The workshop, held in NYSDOT Region 2, consisted of short classroom training in the morning, followed by site visits to four LSF in Region 2 of various ages and vegetation types including willow, evergreen trees and shrubs. Instruction and discussion at each stop focused on the original research conducted as part of this project and how the dynamics of maturing LSF affect snow trapping function over time. This dynamic was illustrated by visiting LSF with a range of ages, plant types, heights and snow storage capacities and explaining how these factors affected the length of the downwind drift and selection of setback distance and other design factors.

Class sizes were planned to be relatively small, up to 25 people in each session. Small class sizes were chosen to allow more interaction and for safety reasons: NYSDOT did not wish to have a large number of people on the right of way. However, more people were able to attend the design class as there was not a safety issue with classroom instruction.

Nearly 110 people attended all of the classes and they helped install four new willow LSF in the landscape in areas known to have blowing snow problems. Feedback received on all the workshops was very positive.

Below is a list of the training workshops undertaken, examples of documentation from the classes, write-ups created after the workshops, field maps and photos of each of the four sites to have a demonstration LSF installed. A brief write-up, link and screenshots of the project website created for information dissemination is also included here.

Class 1: Sessions 1 and 2

NYSDOT Region 3

Tully, New York (Onondaga East Residency)

Design Training, May 27, 2009 College of Environmental Sciences and Forestry Training Center, Heiberg Memorial Forest, Tully, New York

Installation Training, May 28, 2009, West side of Interstate 81, north of Tully exit.

This was the first of the four classes and was held in Tully, New York, south of Syracuse. The class designed and installed a living snow fence on the west side of Interstate 81, for about 1,200 north of the Tully exit.

Class 2: Sessions 1 and 2

NYSDOT Region 5

Design training: October 27, 2009, NYSDOT Regional Offices, Buffalo, New York

Installation training: May 13, 2010, Route 219, Towns of Boston and Concord (Erie South Residency)

Class 3: Sessions 1 and 2

NYSDOT Region 9

Beerston, NY (Delaware South Residency)

Design Training May 25, 2011, Delaware County Soil and Water Conservation District Offices, Walton, New York

Installation Training , May 26, 2011, Route 10, Beerston, New York

Class Four: Sessions 1 and 2

NYSDOT Region 2

Town of Paris (Oneida East Residency)

Design Training October 20, 2011, Regional Crews Conference Room, Utica, New York

Installation Training May 20, 2012, Route 12, Town of Paris

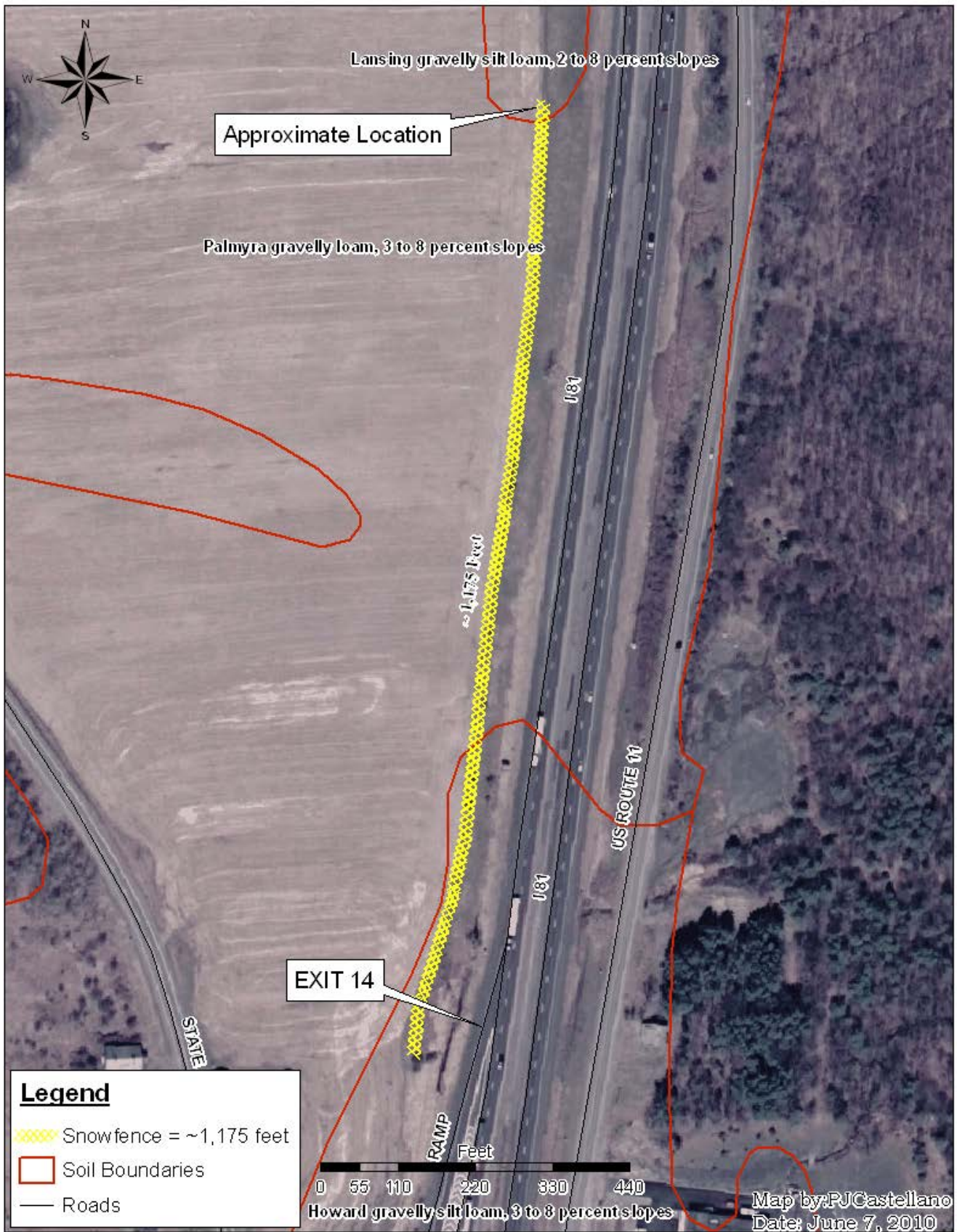
Class Five

NYSDOT Region 2

Field Tour of Existing Living Snow Fences

July 25, 2013 (page 177 of 437)

Class 1
Region 3
Tully, NY
2008-2009









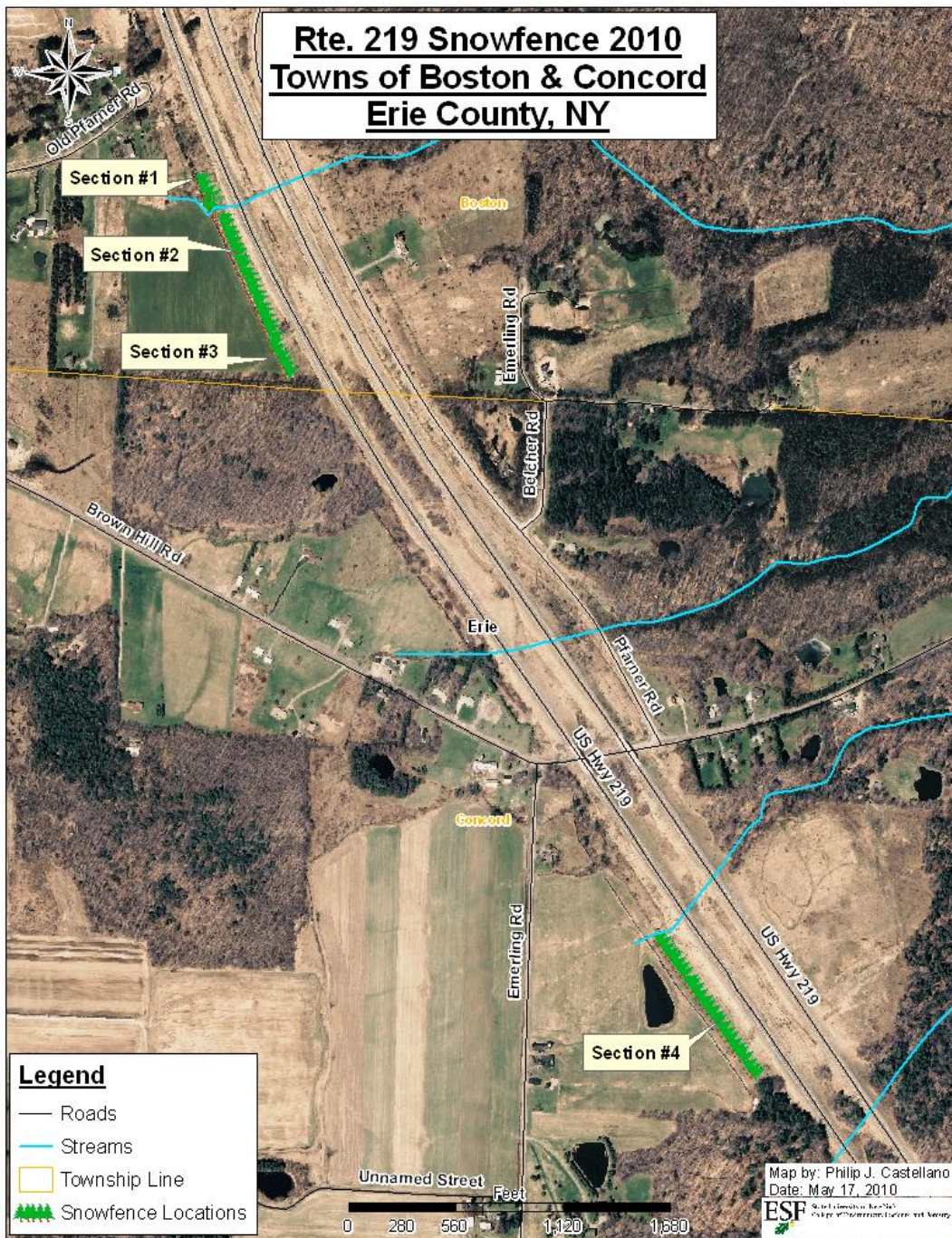
Class 2
Region 5
Hamburg, NY
2009-2010

Living Snow Fence Training in Buffalo, NY (May 13, 2010)

On May 13, 2010, Tim Volk, a researcher from the State University of New York's College of Environmental Science and Forestry (ESF) presented the second of two sessions for NYSDOT staff in western New York on how to install living snow fence. The class was a "train the trainer" session; one objective was to provide attendees with enough information so they could provide living snow fence training when they returned to their Region.

Overview:

The aerial photograph below shows the planting design. The northern section in the Town of Boston has three segments. The southern section in the Town of Concord has a single section.



Graphic by P.J. Castellano, College of Environmental Science and Forestry

Installation Training:

This session started in the classroom at NYSDOT's Buffalo Regional Office with an overview of information on successfully installing a living snow fence. After the overview, the class went to two locations on Route 219 and installed much of the living snow fence to that is planned to replace an engineered snow fence.



The left picture shows the northern location on Route 219, in the Town of Boston, about a mile south of Rice Hill Road interchange, where a snow fence will be replaced by a living snow fence using willows.

The right picture shows a location on Route 219, south of Brown Hill Road in the Town of Concord, where snow blows across the highway and causes significant road icing and crashes. At this location, willows will augment an existing snow fence which is 10 feet tall.

Living snow fence with willows is planted in two parallel rows, with plants in each row slightly offset. The offset allows grown plants to overlap, so the snow has no openings to blow through and reach the highway.

Installation begins with site preparation. A planting area is created by removing weeds, and then by tilling the soil. Weeds can be removed with herbicides or mechanical means. The typical herbicide in this situation has glyphosate for an active ingredient and it will take seven to 14 days for the glyphosate to kill the vegetation.

Next, landscape cloth is set down over the tilled area and secured on the edge with dirt. Tractor attachments are available to roll out the landscape cloth and plow a line of earth along each edge to hold down the cloth, but the securing process can also be done manually if equipment is not available.

After landscape cloth is placed, installation proceeds in an assembly-line manner. Two people set the lines for each row of plants. Then, usually in a procession, one or two people use a paint stick to mark the planting spots, people following behind cut an "x" in the fabric for the willow shoots and then people behind them place the willow shoots in the ground.

Cutting an "x" in the landscape cloth is required. A cut in any other shape will result in the cloth constricting the willow trunk and girdling the plant.

After the site is prepared and the willows are planted, workers come along behind and place wood chips. The wood chips are essential to suppress weeds and to provide moisture if the summer is hot and dry.



Tim Volk presents information on living snow fence installation at a pre-job meeting.



The left picture shows the willow shoots, which are about 24 inches in length. They are kept in cold storage until ready to be used, to prevent sprouting before planting.

The right picture shows researcher Eric Fabio distributing willows along the installation area, in advance, to speed planting.



A large amount of wood chips is needed to mulch the willow planting.



Left picture: Philip Castellano, an ESF researcher, helping set the line for planting.

Right picture: Landscape cloth marked with paint for planting. Also, note how tractor attachment anchors cloth with dirt.



Barb Balcerzak, from Erie South Residency, is cutting the landscape cloth with an "x" pattern in advance of planting the willows.



Left and right pictures: depending on the soil, willows may be placed with a mallet or by hand. In the left picture, Tim Volk installs with a mallet; in the right, John Harvey and an unidentified NYSDOT employee install willows by hand.

Below left: Keith Espinosa installs willows by hand.



Left picture: Equipment bringing mulch to snow fence from roadside.

Right picture: Erie South Residency staff placing mulch, to suppress weeds and to protect plants during summer.

Note: Thanks also to Erie South Residency staff: Jason Bond, Chris Deci, Ron Donhauser, Dan Perlinger, Frank Pinker, Michael Saldana and Gerry Koch for their assistance with site preparation, planting, work zone traffic control, mulch delivery and operation of equipment.

Living Snow Fence Status Since May, 2010

Here is a picture of the willows immediately after the installation in May, 2010:



Here is a picture of the installation on December 1, 2010. The photograph shows how active the snow is at this site. Even with the diminished visibility, it is possible to see that growth has occurred.



Here are two pictures from June, 2011. Two issues are present in these pictures:

- Growth in the northern segment was diminished by deer eating the willows in some sections of the installation. This is unusual in NYSDOT's experience with willow fences. Growth was relatively even in the southern section, with no apparent deer disturbance.
- Growth of adjoining vegetation provides cover for deer and competes with the willows. As will be seen in the photographs after these, the Residency mowed and addressed this concern.



Left photograph taken in northern segment; right photograph taken in southern section, Town of Concord

The following two photographs were taken in September, 2011. The Residency mowed adjoining vegetation and that is helping with growth. In the northern section (top photograph), some willows have grown quite high but the growth is till uneven because of deer eating some of the willows. In the southern section (bottom photograph), the willows are growing at a consistent rate. The willows are the uniform line of green vegetation in the middle of the photograph, behind the brown grass.

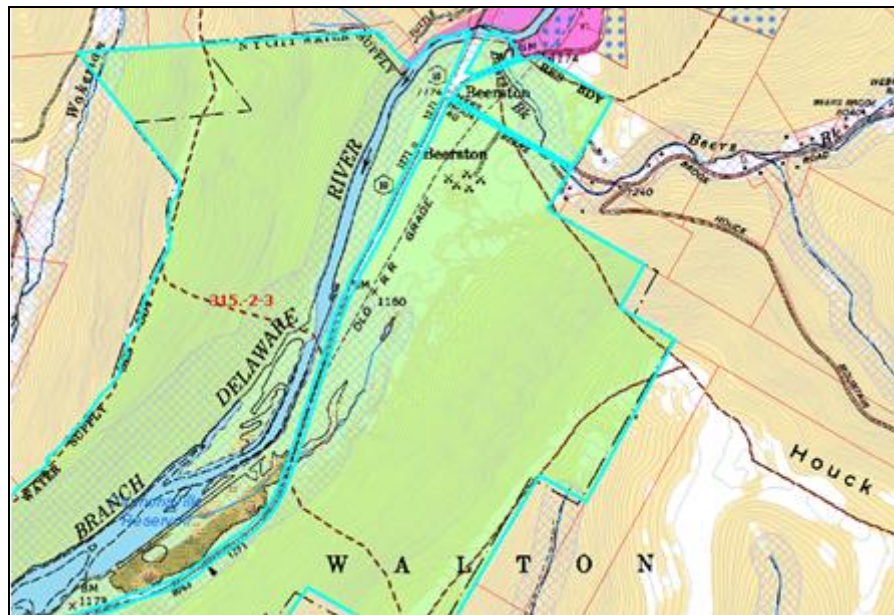


Class 3
Region 9
Beerston, NY
2011

Living Snow Fence Training in Beerston, New York, Region 9: Wednesday May 25, 2011 and Thursday May 26, 2011

In late May 2011, Tim Volk, a researcher from the State University of New York's College of Environmental Science and Forestry (ESF) presented the third of four classes on how to design and install living snow fence.

The issues and solutions at the Route 10 site differ from those at sites in the previous two classes, where snow blows from the west across the highway. When snow blows from the west, the solution is to install a living snow fence upwind of the highway, at a sufficient distance from the highway so snow trapped by the fence does not pile up in the travel lanes.



At the Route 10 site, snow blows west to east, across Route 10, from the direction of the West Branch of the Delaware River. Based on observations by the researcher and residency staff, the snow does not pile up on the road as it blows from in this direction.

The prevailing westerly wind hits the hill and Houck Mountain to the east of Route 10 and then blows west, back towards the road. As the snow is blowing back across the road, it accumulates in the travel lanes. Some snow is considered “far snow,” when the snow is blown across an open area that is several hundred feet or more. While there may be some “far snow” at this site, the majority of the problem is related to what is called “near snow.” When snow is picked up by the wind close to a roadway and deposited on the road, it is referred to as near snow. At the south end of the site, near snow is probably part of the problem because of the embankment of 6 to 12 feet high at the road's edge.

To address this problem, the plan was to install about 1,725 feet of willow cuttings to address the far snow problem. To address the near snow problem at the southern end of the segment, the plan was to plant about potted shrubs from 12 to 18 inches high, in one and two rows for 150 feet at the toe of the embankment at the southern end of the segment.

On Day One, the class convened, in a classroom in the Delaware County Soil and Water Conservation District's headquarters in Walton, New York. Tim Volk provided an overview of the concept of living snow fences and focused on design guidance.

Tim and his colleague Larry Abrahamson finished classroom instruction by lunch time. After lunch, staff met at the living snow fence installation site on Route 10, just south of Beerston.

Looking south, photograph one, below, shows the general area of the plantings, and the hill that reverses the snow back across the road.



The first step in the installation process is to identify the area or areas that will be planted. This is done through the design work explained in the class.

Once the areas to be planted are identified, the next step is to apply an herbicide to kill the vegetation.

Then the installers prepare the soil. The two pictures below show soil preparation. In the first, a tractor with a ripper attachment breaks up the soil and breaks through any hardpan that might be below the soil. It is important to break through the hardpan as willows will be relatively tall and if hardpan prevents the roots from penetrating deep into the ground, the vegetation could topple.

The second photograph shows a rototilling attachment to further smooth out soil. If soil needed amendments, this is the time to undertake the work. Soil amendments were not used at this location.



Photographs above by Justin Heavey,
State University College of Environmental Science and Forestry (SUNY ESF) 2011

In the picture below, the slightly discolored grass on the left side of the landscape cloth shows part of the herbicide treatment to kill the vegetation. A special attachment to the tractor rolled out the landscape fabric and anchored it by tucking it into the dirt on each side of the planting area.



Installation looking north.

Once the landscaping fabric is installed, workers place the unrooted, dormant willow cuttings, using a process similar to a bucket-brigade.

In the first step, workers mark where the cuttings will be placed. As shown in the picture to the left, a straight line, with a rope, is used to mark the rows. Then, as SUNY ESF researcher Justin Heavey is doing in the picture to the right, a worker marks where each willow will be planted.



Next, workers slit the landscape fabric, as Brian Robinson is doing in the picture below, to allow the placement of the willows. The holes must be cut as an “x,” otherwise the landscape fabric can girdle the plants as they grow. Each side of “x” should be three to six inches long.



On this installation, Tim Volk purchased a paper-based landscape material, designed to last 18 to 24 months. The hypothesis is that a durable, paper-based material will last long enough to suppress the weeds - - but will decompose and pose no threat to girdling the plants.

The paper-based landscape cloth did not arrive in time for Day One of the installation. It arrived several days later, in time for planting the second set of the willow shoots, near the southern end of the project, and for the plants at the toe of the slope to address the near snow issue.



Paper-based landscape cloth used for willow cuttings.



Paper-based landscape cloth used with plants intended to control near snow.

Photograph by Justin Heavey. SUNY ESF, 2011

After cutting the landscape cloth, workers put a willow in each hole. Half of the willow should be in the ground, half should be exposed. Rick Ostrander, below, is holding a bundle of willows, about 20 inches long, from this installation.



If the soil is soft, one can push in the willow cuttings, as Tom Story and Tim Volk are doing below.



If soil is harder, a few gentle taps with a mallet are needed to get the willow cutting deep enough, as Lewis Lacey and Walter Geidel, Town of Walton Highway Superintendent, are doing.



At the end of the first day, the class installed all the willow cuttings. This photograph, looking north, shows the extent of the installation.

This photograph also shows how field conditions affect installations. The dried weeds on the left of the picture are Wild Parsnip, a noxious weed that can cause skin burns. For this class, the planting was early enough that the threat of Wild Parsnip was not significant and workers avoided easily detectable plants.



Wood chips help suppress weeds and prevent them from overwhelming willow plantings. Most NYSDOT Residencies do not have the equipment, staff or time to water new plantings. Wood chips also serve to retain moisture as the summer progresses.

For this installation, Delaware South and Sullivan Residencies provided about 160 cubic yards of chips to cover the three planted areas.

Where site conditions allow, the best practice is to use mechanical equipment to place the chips. For productivity, the largest loader that fits in the setting should be used.

On Day 2 of the class, Steve Dufton, the Delaware South Supervisor for this segment of Route 10, assigned an articulated loader and John Letosky, the operator, to help. The bucket on this loader could hold enough chips to mulch 24 feet of the willow cuttings before returning for another load.



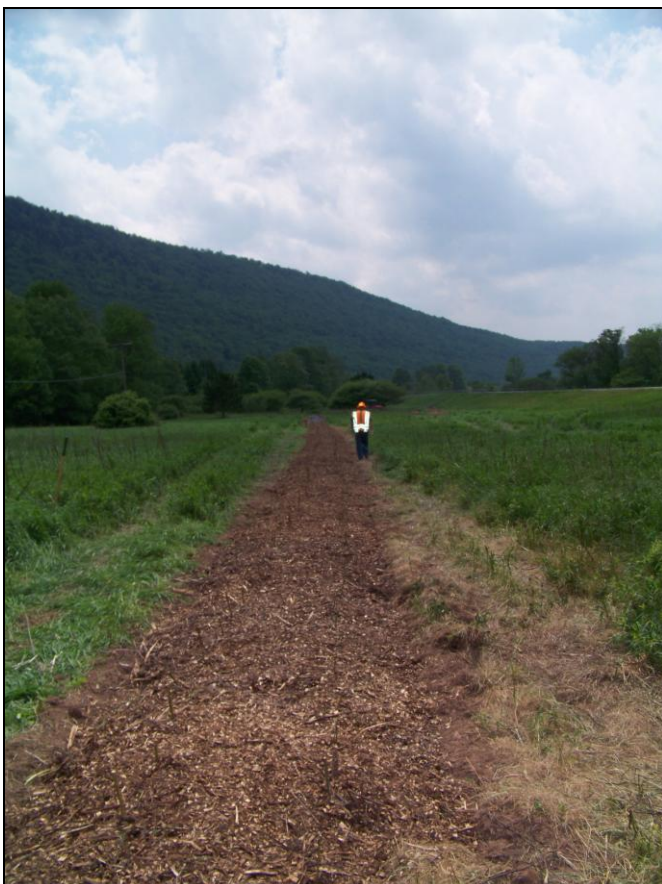
When working with wood chips, it is important to limit the amount of live vegetation in them. A skilled operator will maximize the amount of chips that can be placed in a single trip. In the picture on the left, Tom Story, Everett Cass and Chris Kappeller are unloading chips. In the picture on the right, Peter Norton and Phil Castellano are unloading the chips and trying to keep live vegetation out of the planting.



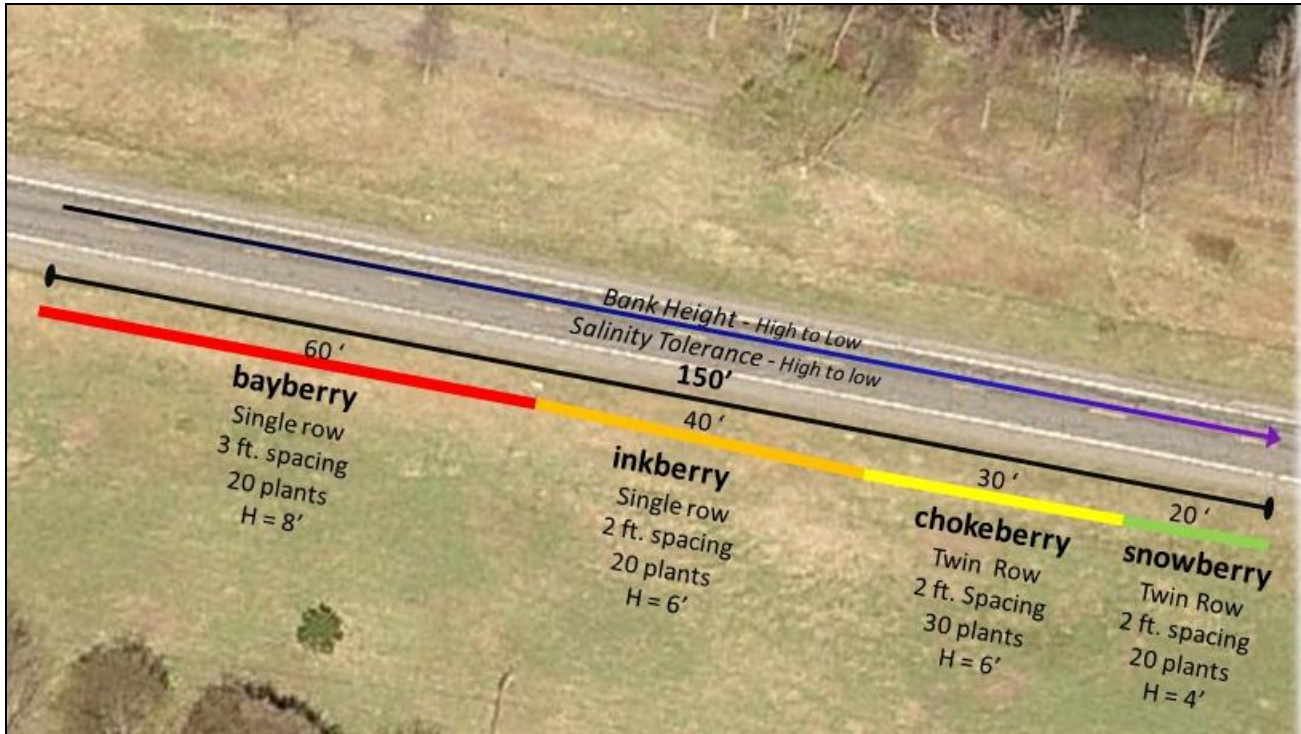
Once the chips are unloaded, workers need to spread them out, to realize the weed control and moisture retention benefits. These pictures show Brian Robinson, Peter Norton, Lewis Lacey, Tom Story, Bob Richter, Paula Bagley and Everett Cass placing chips.



Here are pictures of the completed work as of Day 2:



To address near snow at the south end of the project, bushes were planted at the base of the highway slope. The researchers developed the following planting plan, to guide the work in the field.



Planting Chart by Justin Heavey. SUNY ESF, 2011

For this installation, the bushes were ordered as potted plants. The benefit is that they are larger and have a higher likelihood of survival once planted. When potted stock is ordered, however, the stock must be kept watered and protected before planting, as is shown in the photograph, below:



Photograph by Justin Heavey. SUNY ESF, 2011

Here is a photograph of the bushes, just after planting, with Justin Heavey in the photograph for scale.



The class

Thanks to good site preparation and regular rain since the installation, the willow cuttings are off to a good start. The top picture shows Mike Darder of Delaware South checking the installation 12 days after planting. Note the leaves starting to appear on the willows. The bottom left photograph shows leaves starting to appear on the second group of willows at 10 days later; the bottom right photograph shows growth at 55 days.



On this page and the following are three panoramic photographs of the willow and bush installation 55 days after the planting. A common factor in all the pictures is good weed control. Below are the bushes at the toe of the slope, looking south



In the photographs below, note good willow survival, good weed control and strong growth in the first 55 days. The lower left picture is looking north at the main willow installation. The lower right photograph is looking south at the installation of the southern rows of willows.

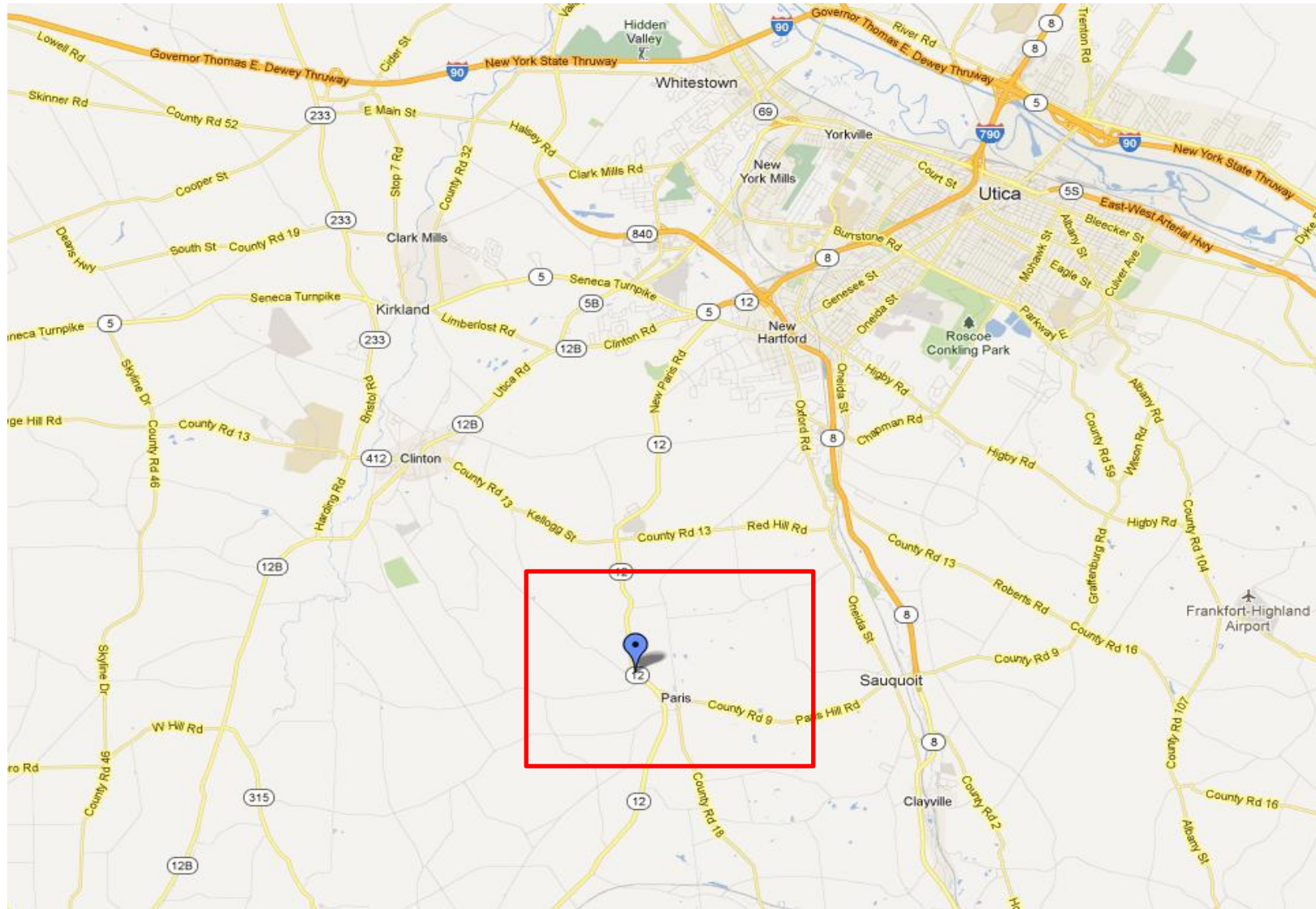


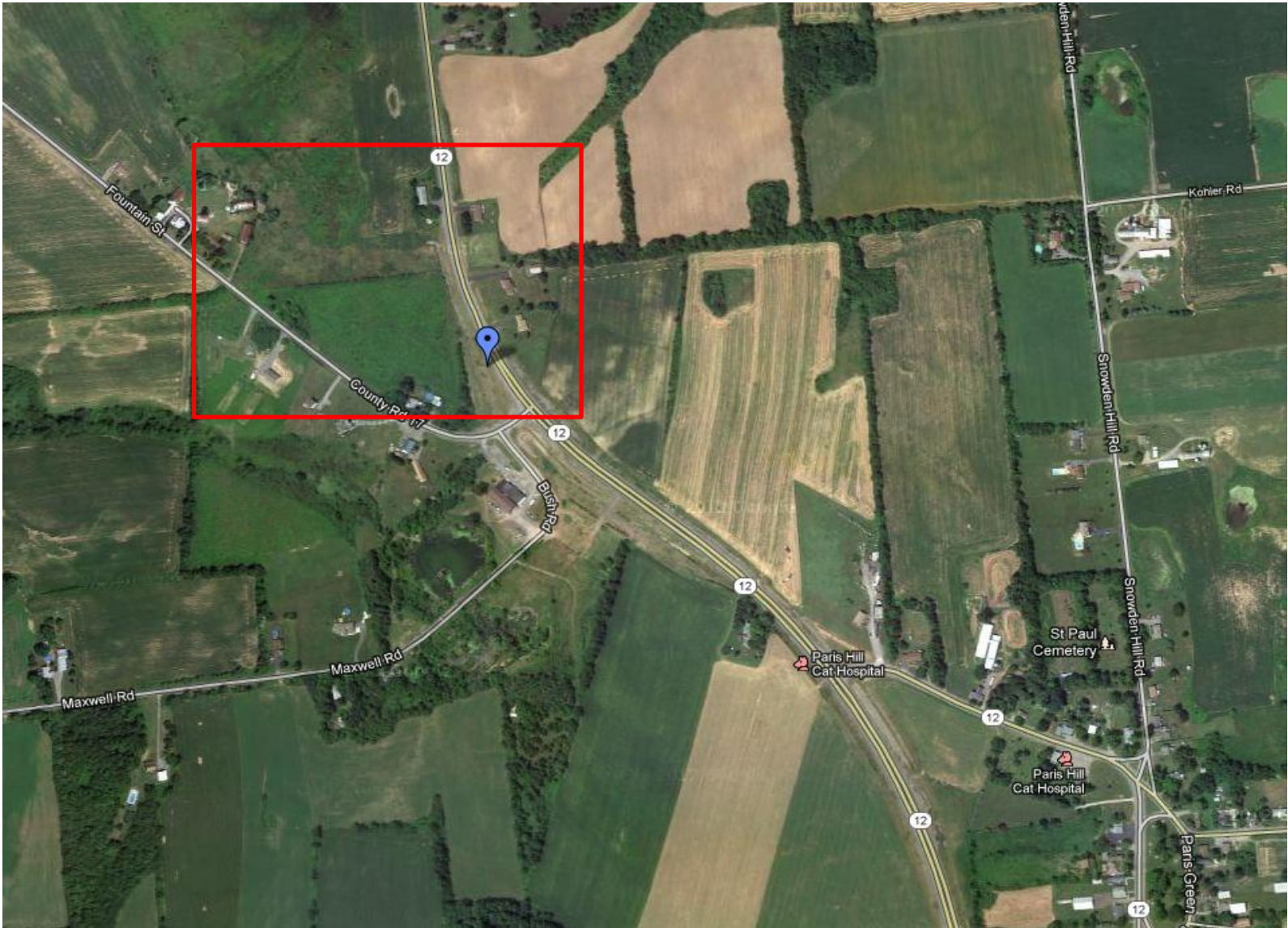
Class 4
Region 2
Paris, NY
2012-2013

Willow LSF Installation: Route 12 - Paris, NY

May 2012



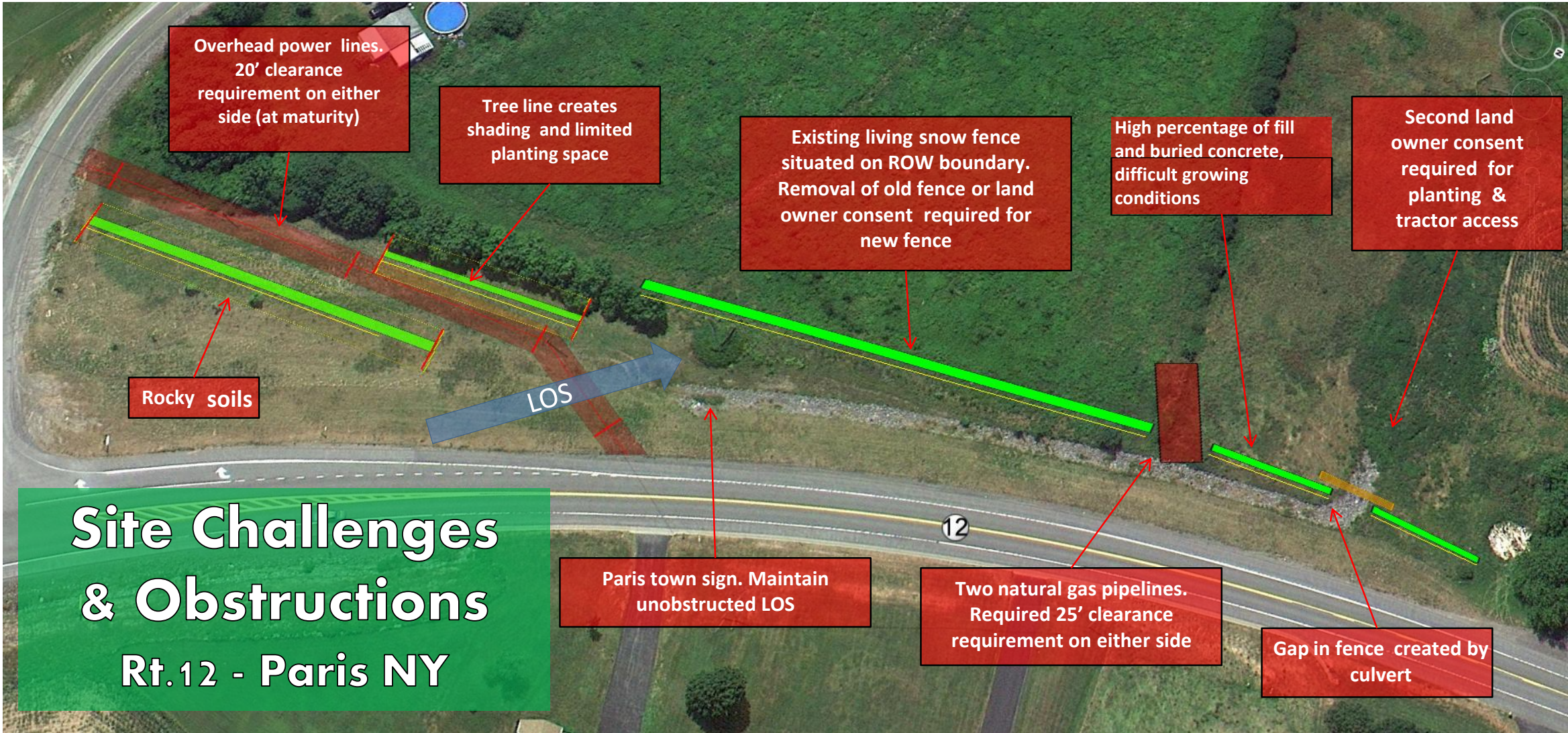


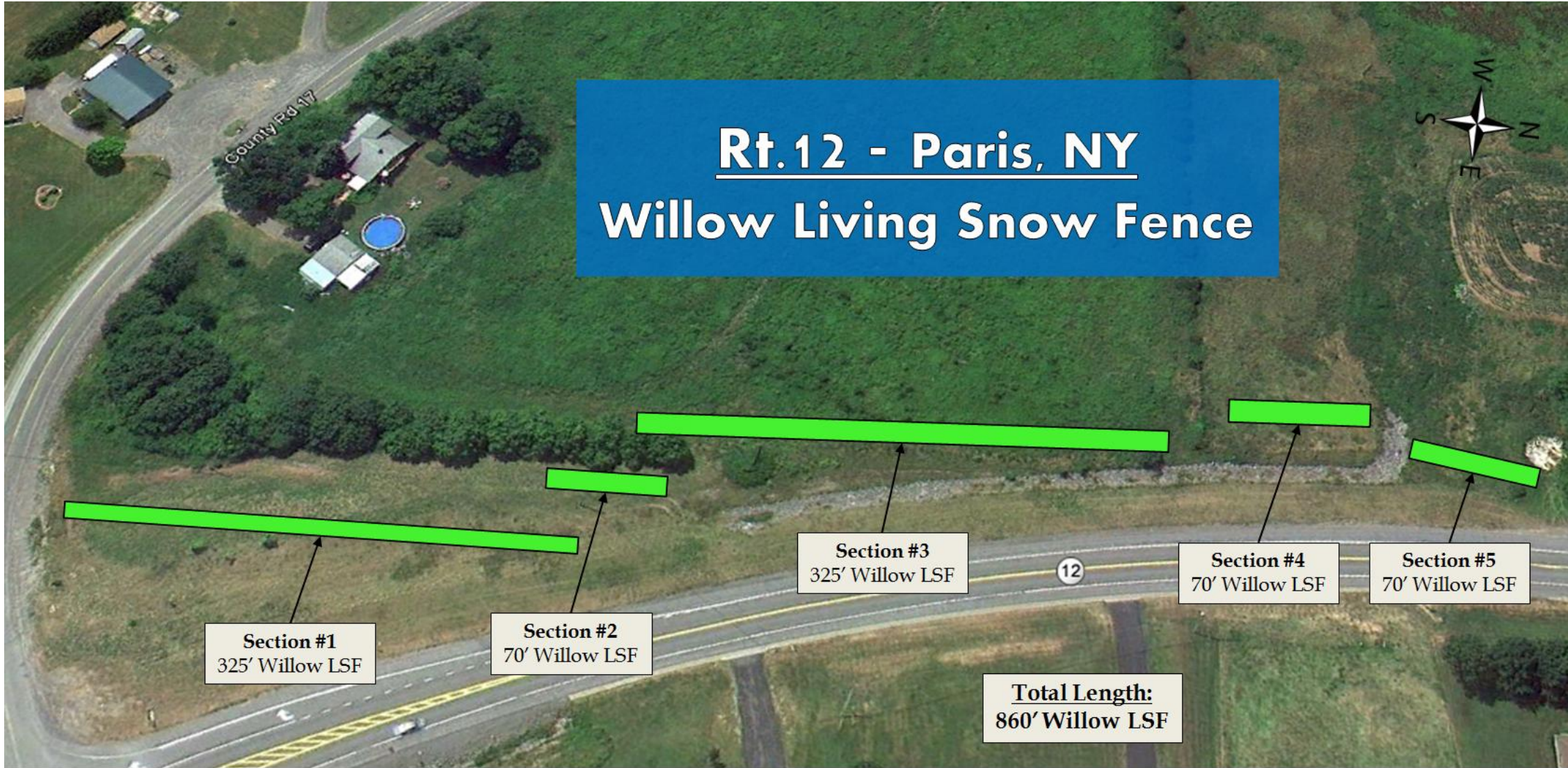


Working with site conditions...

- Tree line (shade)
- Existing snow fences
- Utilities (electric & gas)
- Rocky soils & fill
- Paris town sign
- Ditches, etc.







Class 5
Region 2
Various Locations
August 2013

Research Project C-06-09

Designing, Developing, and Implementing a Living Snow Fence
Program for New York State

Workshop 9

Field Tour of Existing Snow Fences

July, 2013



State University of New York
College of Environmental Science and Forestry



New York State
Department of Transportation

Justin P. Heavey
Dr. Timothy Volk
Dr. Lawrence Abrahamson

State University of New York – College of Environmental Science & Forestry

John Rowen

New York State Department of Transportation

Background

Blowing and drifting snow can reduce highway safety and increase the costs of snow and ice control. Living snow fences are a means of passive snow control that disrupt wind patterns causing controlled deposition of snow in drifts around the fence before it reaches the roadway. Living snow fences are rows of densely planted trees, shrubs, or other vegetation types that act as a porous barrier to the wind. Living snow fences can consist of any vegetation species or combination of species that possess the key characteristics of sufficient height; growth rates; optical porosity; ground level branching pattern; and the ability to survive and achieve optimal development in the environmental conditions at the snow fence site.

Living snow fences of various vegetation types and planting patterns have been installed in various locations across New York State by NYSDOT over the last decade and longer. In recent years, NYSDOT has also collaborated with SUNY ESF on various tasks related to living snow fences as part of research project C-06-09. This project has included basic and applied research aimed at improving the design, installation, and management of living snow fences, and the transfer of this technology to NYSDOT residencies and staff across the state. Eight living snow fence design and installation workshops have been conducted in previous years as part of this project, resulting in the installation of four new living snow fences.

This current workshop is the ninth and final workshop of this project, and is intended to give participants an overview of living snow fence growth and function in the years following installation, and engage participants in discussions about design decisions, fence placement and planting patterns, species, challenges encountered and lessons learned, development and function of living fences over time, and any other pertinent information related to living snow fence plantings. This workshop was originally intended as a winter tour to observe and discuss snow fences in the context of observed snow drifts, but lack of a consistent snow fall and scheduling of NYSDOT snow and ice control staff in the winter months has made a winter workshop with adequate participation difficult to accommodate. The same general purpose of a winter tour is intended for the current workshop however, and the same topics of snow fence function can be discussed in terms of observations of key variables of fence height and porosity, which drive snow trapping function. The consultant SUNY ESF has provided summaries of data from each of the four fences visited in this workshop, which was collected in the preceding winter (2012/2013), to facilitate a more informed and detailed discussion on the structure and function of these living snow fences. Four living snow fences were identified for this workshop and information on each fence is provided in the following pages. A regional map and a proposed route and directions to each site, starting from Oneida East Residency, are provided at the end of this handout. Also provided are summaries of data collected from a larger statewide sample of living snow fences, the models of snow trapping function used in this analysis, and sources of more information.

Stop #1: One year old shrub-willow living snow fence

Route 12 SB Paris, NY Region 2 Oneida County Approximate reference marker: 12 260 41119 Nearest crossroad: Fountain St

Site History: NYSDOT and SUNY ESF collaborated to install a shrub-willow living snow fence on Route 12 in Paris, NY in May 2012. The plants in this location have shown excellent growth and survival rates over the first growing season. The fence is on track to achieve functional height and porosity levels by the second or third winter after planting, largely a result of thorough site preparation and follow-up maintenance. The site had several design challenges and planting obstructions that had to be addressed (see diagram on page 5). Some non-traditional site preparation and maintenance techniques have also been implemented at this site.

Planting Information

Year Installed	Fence Age	Vegetation Type	Species/Cultivar	Plant Spacing	Number of rows	Row Spacing	Fence Length	Fetch Distance
2012	1	shrub-willow	varieties "SX64" and "Fishcreek"	2 ft	2	2.5 ft	5 Sections Total 860 ft	900 ft

Snow Trapping Function (Winter 2012/2013*)

Fence Height	Observed Porosity	Snow Storage Capacity of Fence	Annual Snow Transport at Site	Minimum height requirement	Fence Setback Distance	Required Setback at minimum fence height	Predicted drift length at current height and porosity
5 ft	90%	<1 ton/ft	3 tons/ft	4 ft	85 ft	100 ft	110 ft

*Note: Fetch, setback, height, porosity, and capacity values represent measurements taken on section #3 in winter 2012/2013. Numbers rounded for clarity.

Discussion Topics

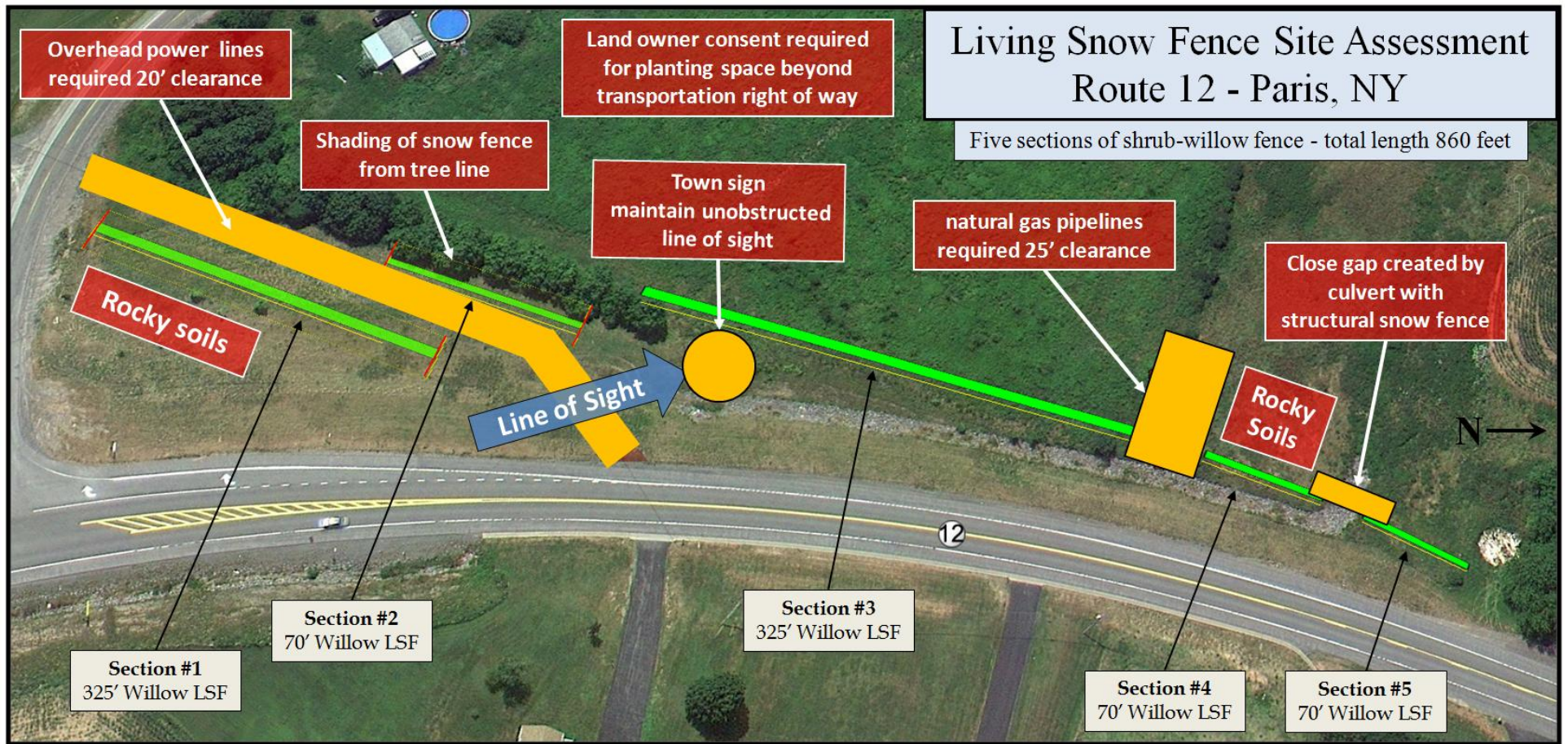
- Structure and Function over time
 - o (See Figures 10 – 14)
- Installation, monitoring, and maintenance
 - o Mowing & deer repellent
- Design challenges and solutions
- Biodegradable landscape fabric & pins
- Coppicing or not (benefits/drawbacks)



Figure 1: Shrub-willow snow fence at Route 12 Paris in May, 2013 - Photo by Justin Heavey



Figure 2: Aerial photo showing locations of shrub-willow snow fence sections planted along Route 12 in Paris, NY



Figures 3: Diagram of fence sections and site challenge for Paris, NY. Diagram by Justin Heavey

Stop #2: Three year old Norway spruce living snow fence

Route 28 SB Columbia, NY Region 2 Herkimer County Approximate reference marker: 28 2304 1067 Nearest crossroad: Horseshoe Lane

Site History: This living snow fence was planted in approximately 2010 by NYSDOT, replacing a structural fence installation. The fence has good height growth, low porosity, and 100% survival. It has one relatively short section, and a dense triple row planting pattern. Fence is installed on private property. A five year land easement was arranged with the land owner after a visualization of the fence was provided. Fence has been reported work well by local NYSDOT staff.

Planting Information

Year Installed	Fence Age	Vegetation Type	Species/Cultivar	Plant Spacing	Number of rows	Row Spacing	Fence Length	Fetch Distance
2010	3	Evergreen tree	Norway spruce	10 ft	3	7 ft	220 ft	2000 ft

Snow Trapping Function (Winter 2012/2013*)

Fence Height	Observed Porosity	Snow Storage Capacity of Fence	Annual Snow Transport at Site	Minimum height requirement	Fence Setback Distance	Required Setback at minimum fence height	Predicted drift length at current height and porosity
9 ft	30%	20 ton/ft	5 tons/ft	4 ft	170 ft	140 ft	40 ft

*Note: height, porosity, and capacity values represent measurements taken in winter 2012/2013. Numbers rounded for clarity.

Discussion Topics

- Norway spruce for living snow fences
- Density of conifer fences
- Number of rows
- Amount of space required
- Setback distance
- Size of trees at installation
- Rapid functionality (landscape effect)
- Performance of living fence compared to structural
- Successfully working with landowners for living snow fences



Figure 4: Norway spruce living snow fence in winter 2012/2013 - Photo by Justin Heavey

North^



Figure 5: Aerial photo of Norway spruce fence along Route 28 Columbia, NY

Stop #3: Eight year old honeysuckle shrub living snow fence

Route 167 SB Manheim, NY Region 2 Herkimer County Approximate reference marker: 167 2302 3024 Nearest crossroad: Lamanna Rd

Site History: This living snow fence was planted in approximately 2005 by NYSDOT. The fence has shown fair height growth and high survival, but optical porosity is higher than desired. Land for planting was acquired through a verbal agreement with the land owner. NYSDOT landscape architects designed and installed the fence. Fence has been reported work well by local NYSDOT staff.

Planting Information

Year Installed	Fence Age	Vegetation Type	Species/Cultivar	Plant Spacing	Number of rows	Fence Length	Fetch Distance
2005	8	Ornamental shrub	Arnold's Red Honeysuckle	3 ft	1	600 ft	675 ft

Snow Trapping Function (Winter 2012/2013*)

Fence Height	Observed Porosity	Snow Storage Capacity of Fence	Annual Snow Transport at Site	Minimum height requirement	Fence Setback Distance	Required Setback at minimum fence height	Predicted drift length at current height and porosity
7 ft	60%	15 ton/ft	2 tons/ft	3 ft	125 ft	80 ft	25 ft

*Note: height, porosity, and capacity values represent measurements taken in winter 2012/2014. Numbers rounded for clarity.

Discussion Topics

- Ornamental shrubs
- Bottom gap
- Single row
- Size of planting stock used
- Cornfield planting



Figure 6: Honeysuckle living snow fence in winter 2012/2013 - Photo by Justin Heavey



Figure 7: Aerial photo of honeysuckle living snow fence along Route 167 in Manheim, NY

Site History: This living snow fence was installed in approximately 1982 and is one of, if not the largest and oldest living snow fence in the state. This presents an interesting and unique opportunity to observe a fence planted with large growing evergreen trees, many years after planting. Land for this fence was acquired and design was conducted via a highway reconstruction project. Fence has been reported work well by local NYSDOT staff.

Planting Information

Year Installed	Fence Age	Vegetation Type	Species/Cultivar	Plant Spacing	Number of rows	Row Spacing	Fence Length	Fetch Distance
1982	31	Evergreen tree	Norway spruce and white spruce	25 ft	2	10	600 ft	2500 ft

Snow Trapping Function (Winter 2012/2013*)

Fence Height	Observed Porosity	Snow Storage Capacity of Fence	Annual Snow Transport at Site	Minimum height requirement	Fence Setback Distance	Required Setback at minimum fence height	Predicted drift length at current height and porosity
45 ft	5%	400 ton/ft	5 tons/ft	4 ft	110 ft	135 ft	20 ft

*Note: height, porosity, and capacity values represent measurements taken in winter 2012/2013. Numbers rounded for clarity.

Discussion Topics

- Oldest known living snow fence?
- Originally intended as living snow fence?
- Large plant spacing
- Species selection
- Capacity/transport ratio and porosity
- Drift length
- Space requirements



Figure 8: Norway and white spruce living snow fence in fall 2012 - Photo by Justin Heavey



Figure 9: Aerial photo of Norway spruce and white spruce living snow fence along Route 167 in Manheim, NY

Living Snow Fence Structure and Function Changes over Time

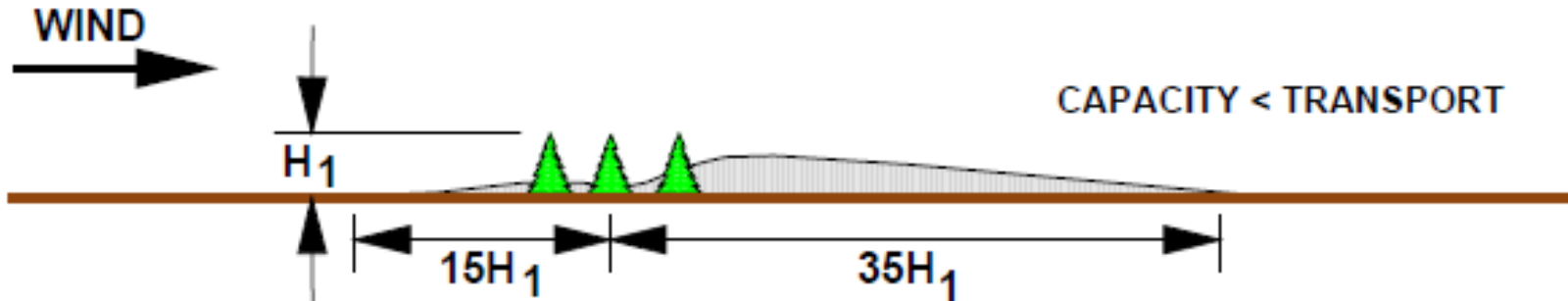


Figure 10: When fence capacity is *less than or equal to snow transport*, the drift length extends to the maximum distance of $35H$, or thirty five times the height of the fence
 Diagram from (Tabler 2003)

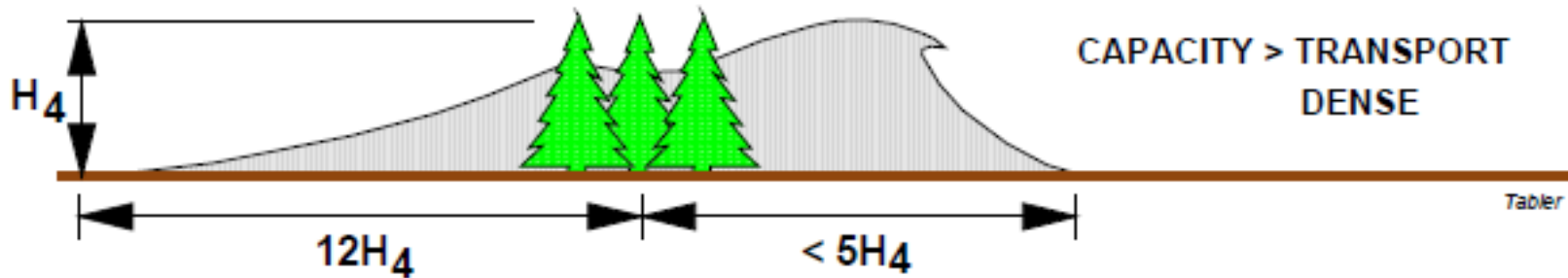


Figure 11: When fences mature and grow to large heights, fence **capacity becomes greater than snow transport**, the drift is reduced to some fraction of the maximum, and the setback distance can be less than $35H$
 Diagram from (Tabler 2003)

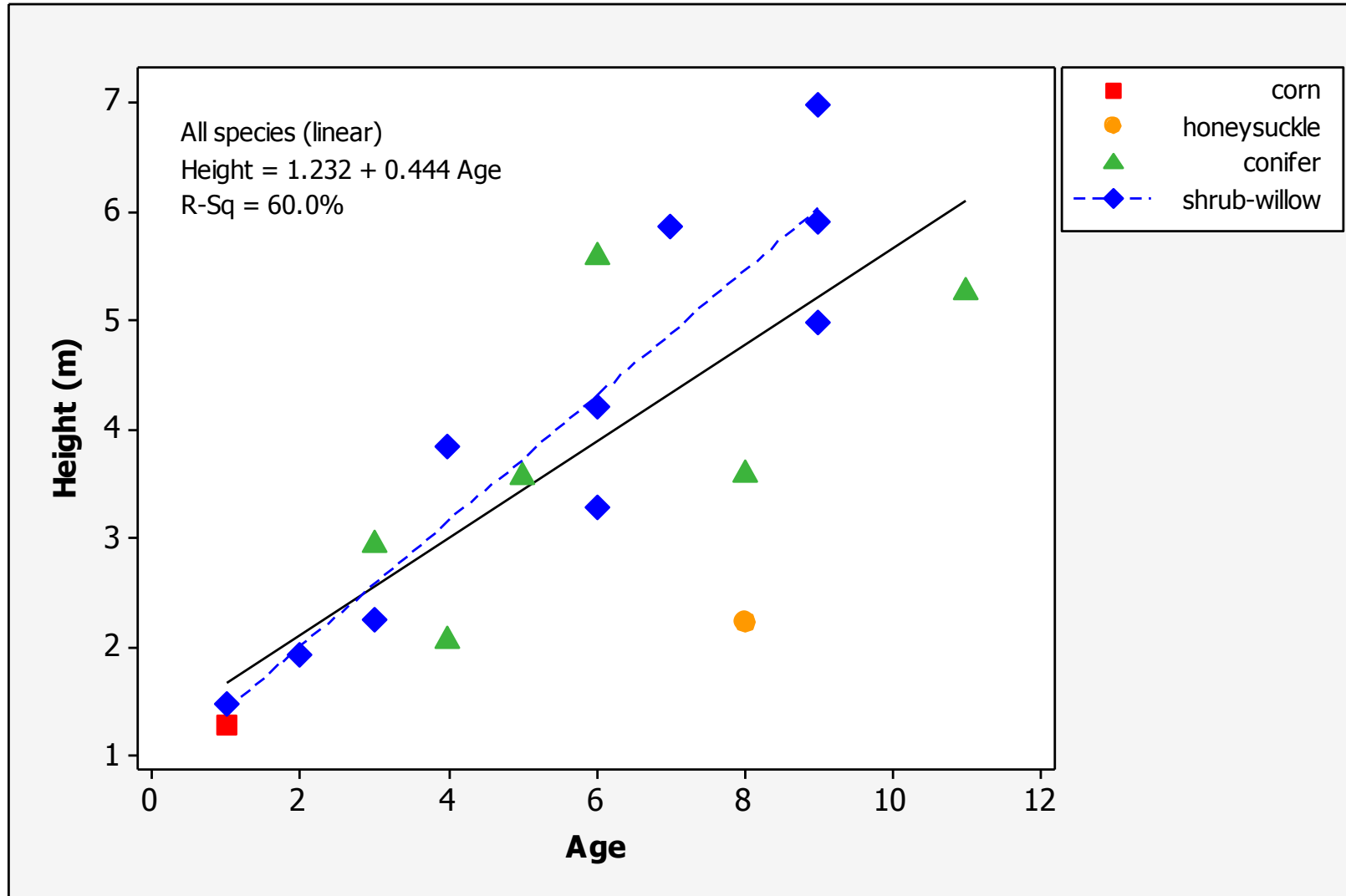


Figure 12: Age versus height (in meters) of 18 living snow fences of various species in New York State, grouped by vegetation type. Height increases linearly with time when best management practices are employed.

Graph by Justin Heavey

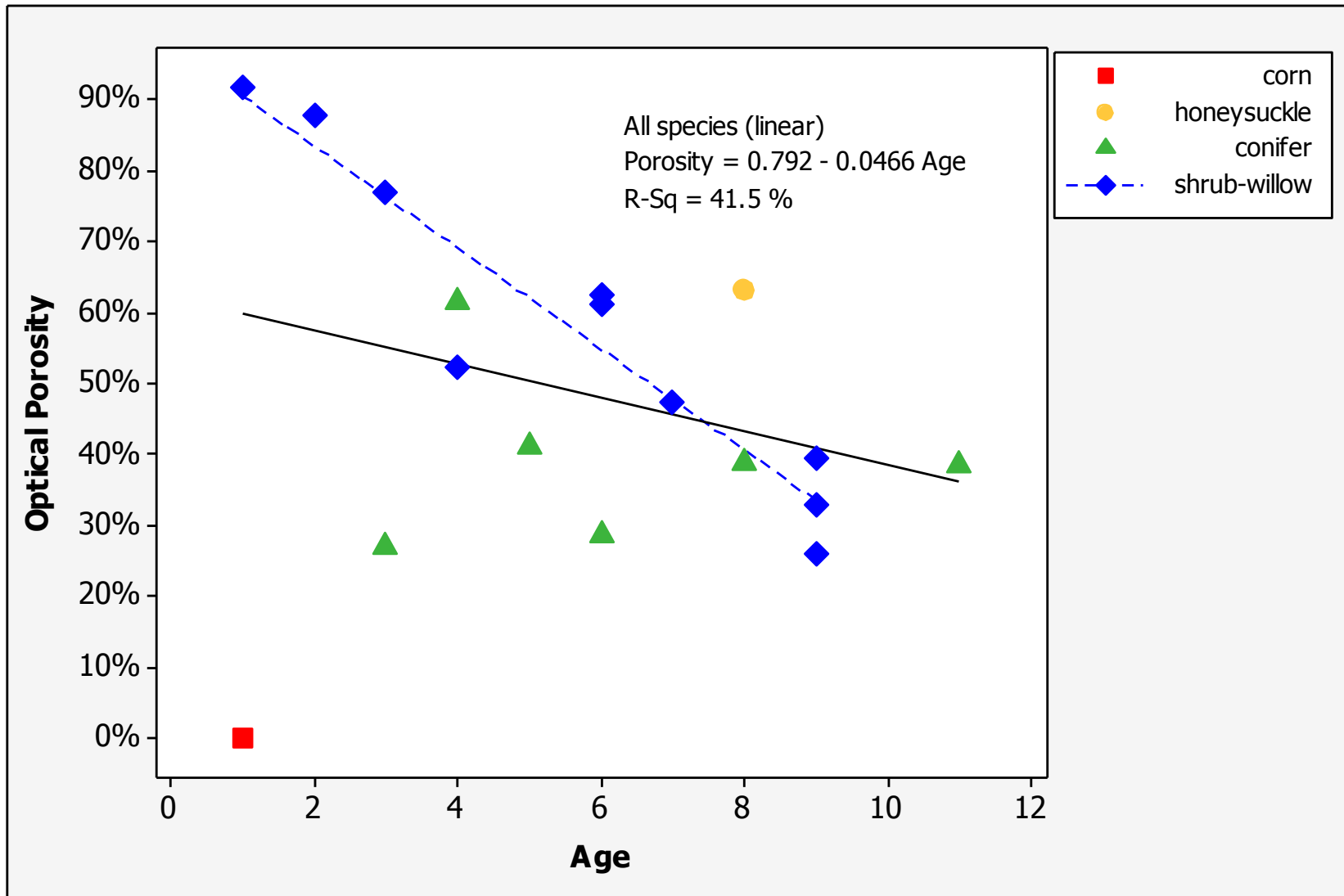


Figure 13: Age versus optical porosity of 18 living snow fences of various ages and species in New York State grouped by vegetation type. Porosity decreases linearly with age when best management practices are applied.

Graph by Justin Heavey

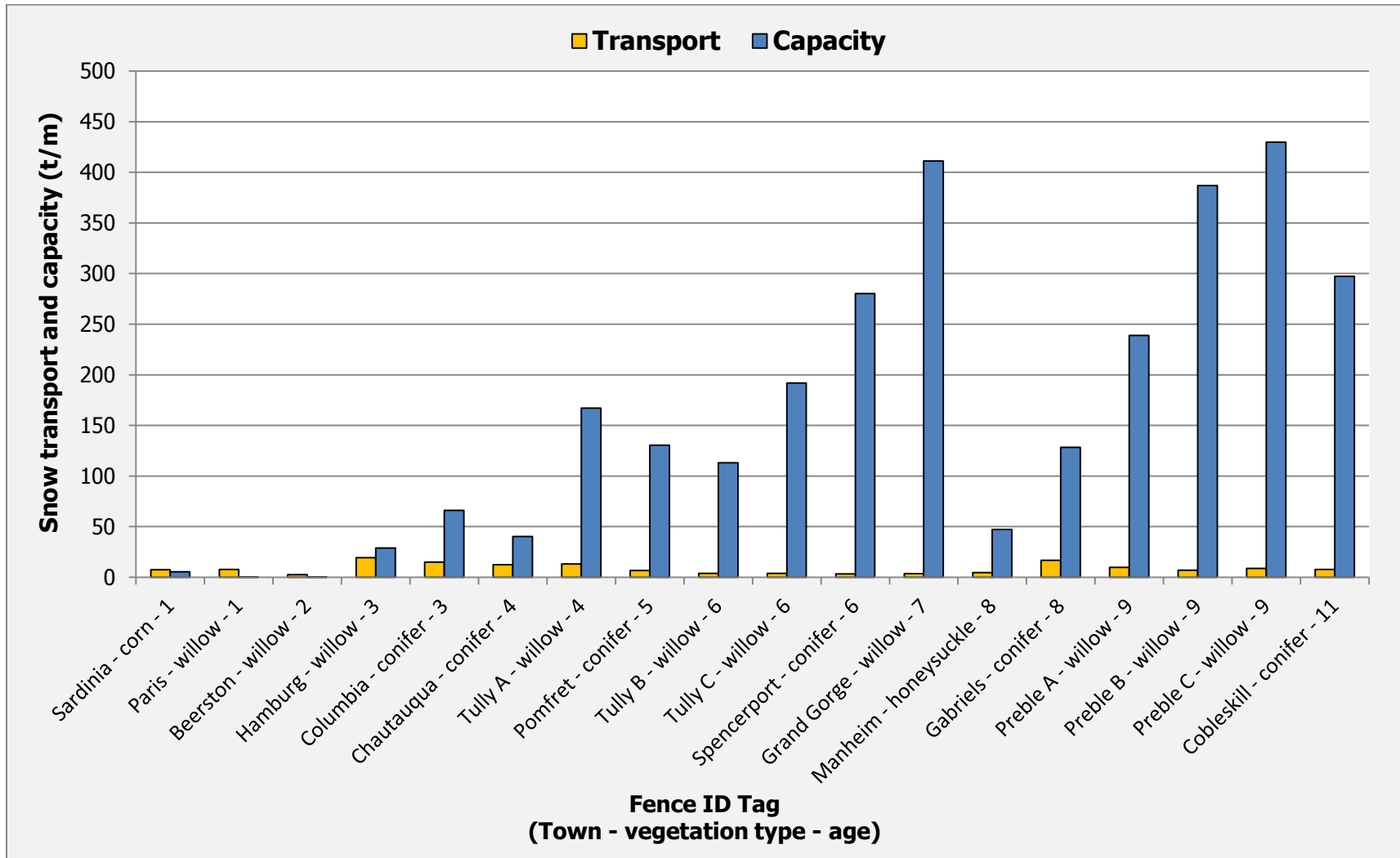


Figure 14: Fence capacity relative to the quantity of snow transport at each site for 18 living snow fences of various species and ages in New York State. Capacity greatly exceeded transport for all fences age three and older.

Chart by Justin Heavey

Models and Sources

Average Annual Snow Transport in New York State (Q)

$$Q = 1500(0.17)(S_{we,AS})(1-0.14^{F/3000})$$

Where:

Q is average annual snow transport in t/m

(0.17) is the assumed snow relocation coefficient (C_r)

($S_{we,AS}$) is the water equivalent of snowfall over the accumulation season in meters

F is the fetch distance in meters

Snow Storage Capacity of a living snow fence (Q_c)

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

Where:

Q_c is the snow storage capacity of the fence in units of t/m

P is the observed optical porosity value of the fence

H is observed height of the fence in meters

Required Height of the fence (H_{req})

$$H_{req} = (Q/8.5)^{0.455}$$

Where:

H_{req} is the required height of the fence in meters

Q is the average annual transport in t/m

Predicted Setback distance (D_{35})

$$D_{35} = (\sin\alpha)35H_{req}$$

Where:

D_{35} is the predicted setback distance in meters

α is the degrees of the prevailing winter wind angle relative to the roadway. α was assumed to be 90° in all cases

H_{req} is the required height of fence in meters

Predicted Drift Length of the downwind drift

$$L = \{[10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3\}(12 + 49P + 7P^2 - 37P^3)(H_{req})$$

Where:

L is the length of the downwind drift in meters

Q is the estimated snow transport at the fence in t/m

Q_c is the estimated fence capacity in t/m

P is the observed fence porosity

H_{req} is the required height of the fence based on the transport quantity (Q)

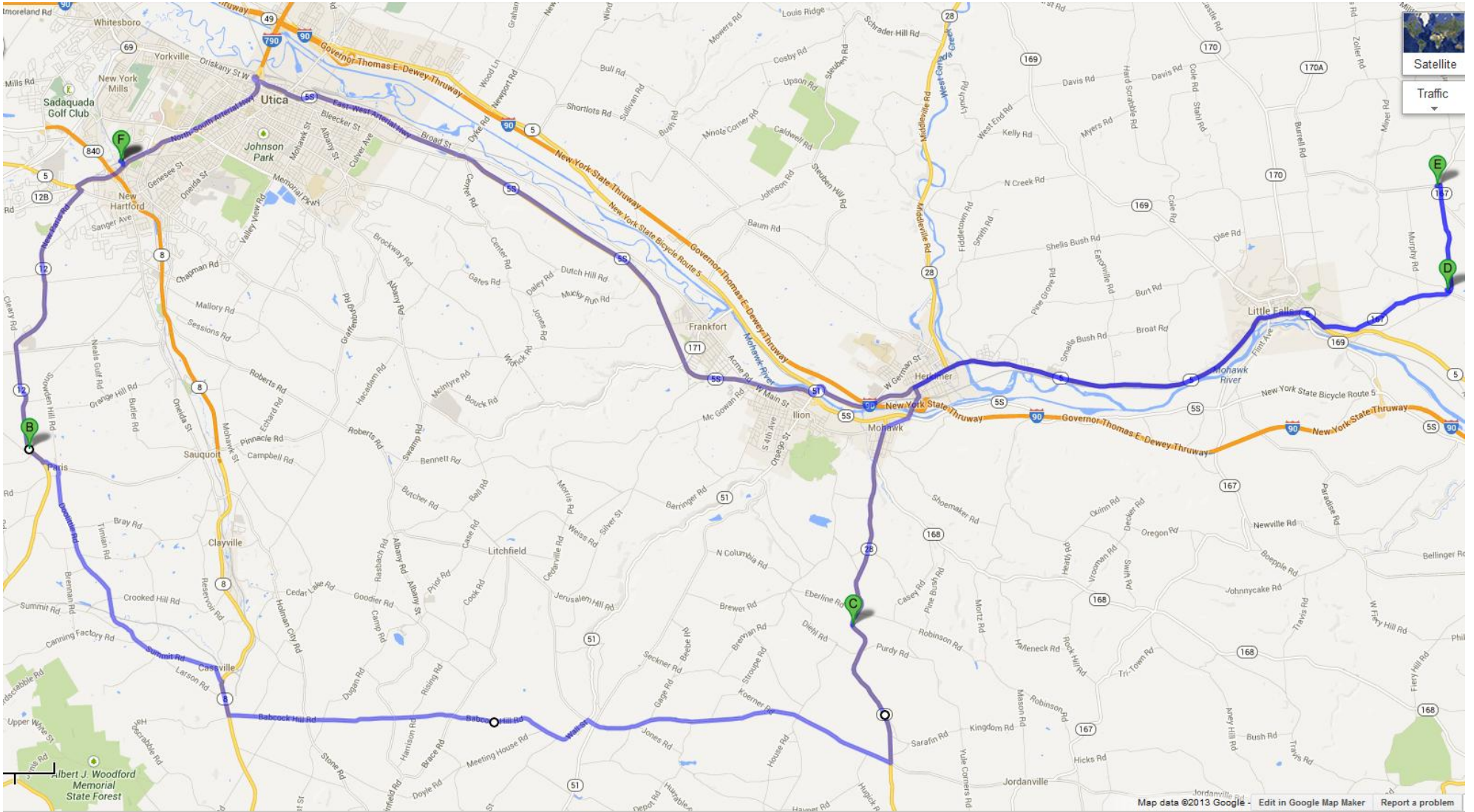
Sources:

Tabler, R.D. 2000. *Climatological analysis for snow mitigation in New York State*. Tabler and Associates. Niwot, CO.

Tabler, R.D. 2003. *Controlling blowing and drifting snow with snow fences and road design*. Tabler and Associates. Niwot, CO.

More information and resources for living snow fences is available online at www.esf.edu/willow

Google Map of Suggested Workshop Tour Route

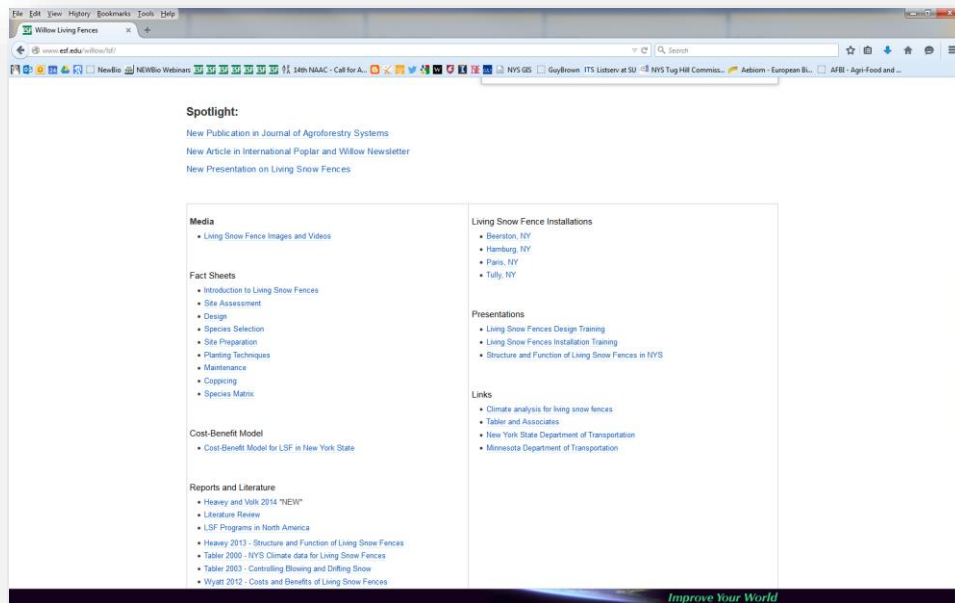
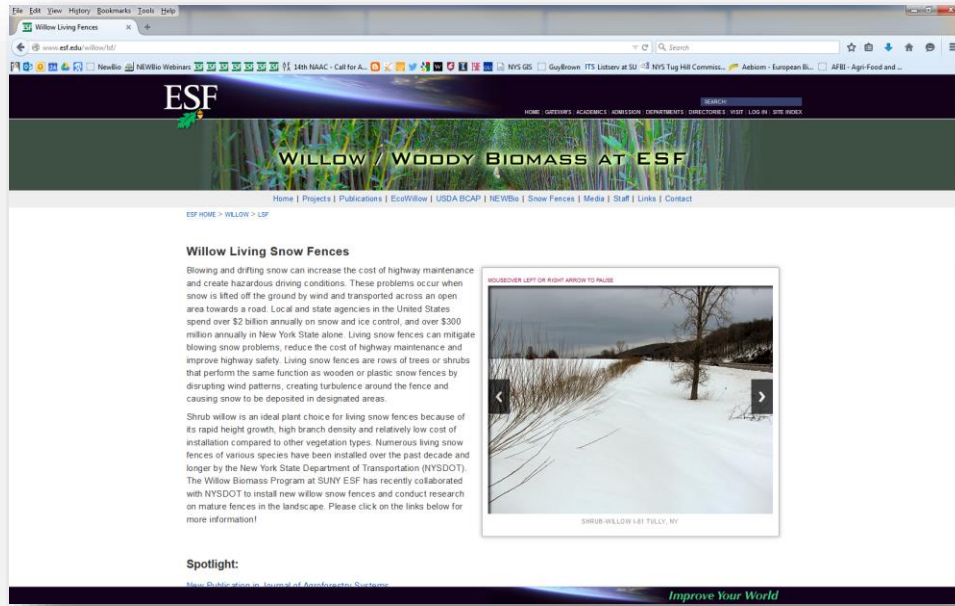


2B-8

Project Website

www.esf.edu/willow/lsf

As the final subtask of Task 2, a webpage was created and hosted by SUNY-ESF. This website provides an introduction to LSF and the work conducted in this project; photo slideshows of the trainings and installation of LSF; photos of LSF throughout NYS studied in Task 3; and links to the fact sheets, presentations, cost benefit model and other materials produced in this project. The website can be accessed by NYSDOT employees and the general public at (www.esf.edu/willow/lsf). Screen shot of the website are provided below.



Task 3-A: Protocol for Pre- installation Field Measurements

Research Project C-06-09

Designing, Developing and Implementing a Living Snow Fence Program for New York State

Task 3-A1 & 3-A2

Protocol for Pre-Installation field Measurements for Prospective Living Snow Fence Sites in New York State

August, 2013



State University of New York
College of Environmental Science and Forestry



New York State
Department of Transportation

Justin P. Heavey

Dr. Timothy Volk

Dr. Lawrence Abrahamson

State University of New York

College of Environmental Science & Forestry

John Rowen

New York State Department of Transportation

Background

Site assessment and pre-installation measurements are important first steps in the establishment and long-term success of living snow fences. Once a prospective site has been selected for a living snow fence installation, site assessment and measurements inform the design and planting phases. The following protocol offers a general methodology for living snow fence site assessment and measurement that can be modified as needed by the design team based on the specifics of the site and design goals.

This paper specifies some measurements in English units and some in metric units. When metric units are specified, please calculate in metric units as metric units will be required in subsequent steps in subsequent equations.

Identify the Problem and Evaluate the Site

- ✓ Identify the problem by determining the source of blowing snow and potential solutions using living snow fences. Refer to Tabler (2003) chapter 4 for more specific information on blowing snow problem identification.
- ✓ Collect accounts of winter road conditions and drifting patterns. In collecting accounts, ensure that information is gathered from workers who plow or maintain a given highway segment. Such people are often the most familiar with the snow problem at a site. If possible, the living snow fence design team should observe winter road and drifting conditions firsthand.
- ✓ Thorough site assessment includes a combination of remote sensing using geographic information software (GIS) and site visits in the field. As site evaluation proceeds, numerous site visits are generally required before installation of the snow fence begins. Make at least one visit to the prospective site with as many stakeholders as possible (New York State Department of Transportation (DOT) staff, contractors, landowners, etc). Discuss any site-specific challenges and opportunities as a group while in the field with all stakeholders (Figure 1).
- ✓ A variety of challenges to continuous living snow fences can exist at a site and conditions vary widely from site to site. Challenges are anything that would impede or complicate the installation,

short, and long-term growth of the fence. Challenges can be above ground such as overhead utility lines, or below ground such as rocky soils. Examples of site challenges identified at a prospective living snow fence site in Paris, NY, are provided in Figure 2.



Figure 1: Discussion among stakeholders of potential site challenges and opportunities during a field investigation of a prospective living snow fence site in Hamburg, NY, in 2009

- ✓ Identify any potential permit requirements or regulatory agency concerns before proceeding to the next steps. For example, utility rights of way require certain clearance distances free of vegetation (including living snow fences) and environmentally sensitive areas, such as watersheds or wetlands, often restrict the use fertilizers and herbicides.

- ✓ During the initial site evaluation, consider the existing vegetation on site, topography, fences, buildings, open spaces and any other factors that would affect wind patterns or plant growth. Refer to Tabler (2003) chapter 4 for more specific information about landscape features that can be detrimental or beneficial to living snow fence function.

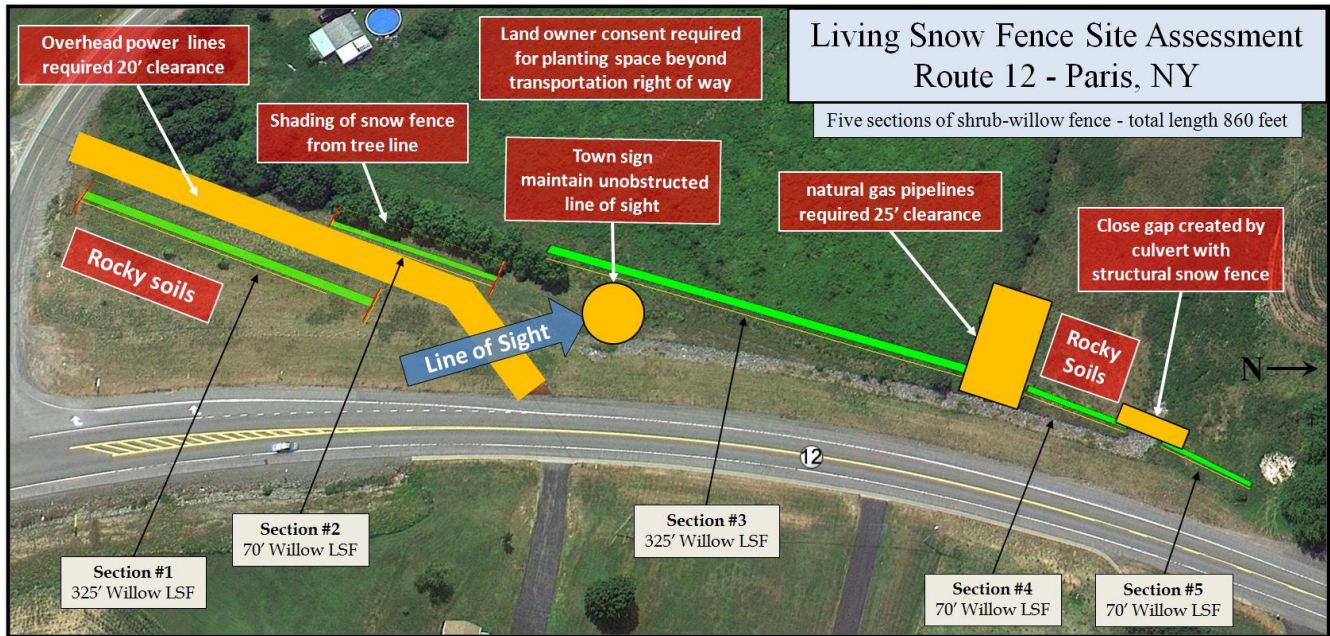


Figure 2: Challenges to snow fence installation (red boxes) identified during the site assessment phase of a prospective living snow fence installation in Paris, NY

Examine Aerial Photos of the Snow Fence Site

Examining aerial photographs of a prospective living snow fence site and the surrounding land will assist in the site analysis and measurement by providing an overview of the site, and context of the landscape around the fence including fetch (**F**), the area *upwind* of the fence that contributes to the blowing snow problem. Examining aerial photographs before field visits can help determine the best parking and access route to the fence. Aerial photos provide a bird's-eye view of the site and can show things that may not be readily visible when on the ground, but may be important to the analysis of the snow fence and site. An example of an aerial photo of a living snow fence site is provided in Figure 3.

The Google Earth software program is a free, user-friendly GIS program that often has the most up to date aerial photos. Living snow fence sites can be easily viewed from multiple angles and resolutions in this software. Site locations can be “bookmarked” for easy identification and further analysis. Distances, such as the fetch distance (**F**), and elevations can also be quickly and easily measured in Google Earth and shapes can be marked on the landscape and printed as aerial maps that can assist in the next steps of site analysis. Examining aerial photos of living snow fences can frame the

snow fence in the context of the important site characteristics that contribute to the blowing snow problem.

Another useful feature of Google Earth is that, for most locations, aerial photos from previous years can be easily accessed. This feature can provide valuable information on recent land use history. If possible, supplement historical aerial photos with information about land use history gathered from land owners, local residents or NYSDOT staff members who are familiar with the location.



Figure 3: Aerial photo of an existing living snow fence site from the Google Earth software program. The existing living snow fence is indicated by the tree icon for reference.

When examining aerial photos, consider the site in the context of the basic elements of living snow fence design. Figure 4 illustrates the basic elements of a snow fence site. At the top of this Figure is a row of houses that indicates an obstruction to the wind. Snow transport is assumed to start downwind of the houses. The *fetch area* is the open area upwind of the *protected roadway* where snow is lifted off the ground and transported by the wind toward the roadway. The *prospective snow fence* will disrupt the wind and cause snow deposition around the fence. *Setback* is the distance between the

fence and the *protected roadway*, required to prevent drifts from building on the roadway to be protected by the fence.

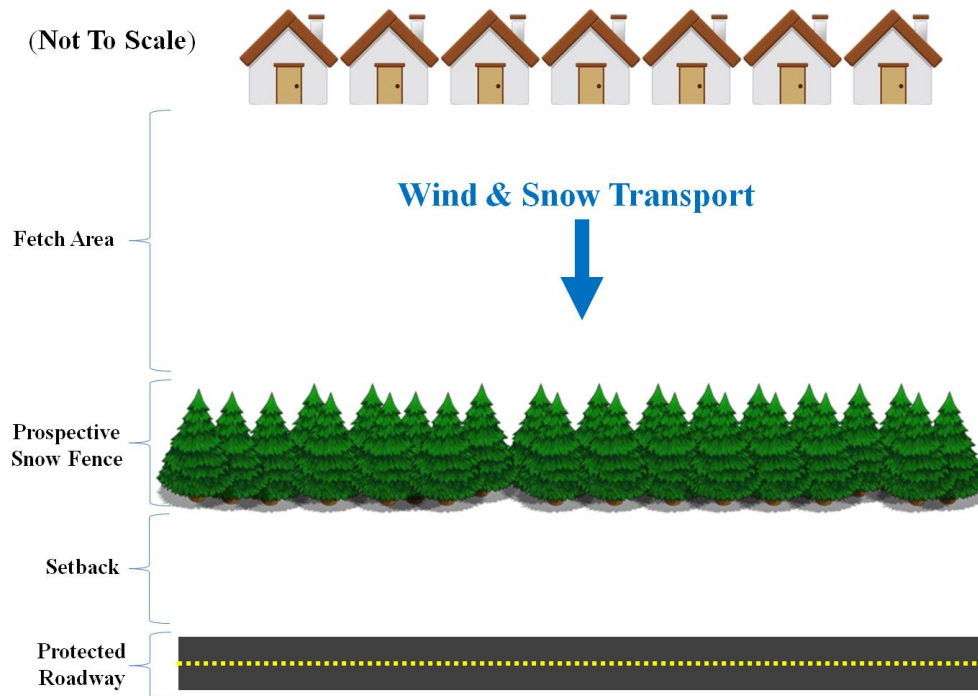


Figure 4: Diagram of living snow fence site showing the basic elements that influence site analysis, fence design and snow control

Estimate or Measure Climate Variables

Estimating or measuring climate variables that influence snow transport is an important step in site analysis for living snow fences. The primary resource for estimating climate variables comes from Tabler (2000) “*Climatologic analysis for snow mitigation in New York State*”. This report provides equations to model key variables for living snow fence design. The models in this report were developed using long-term climate data, weather station observations and other climate models. This resource provides the equations necessary to estimate the key variables of: snowfall over the drift accumulation season; the predominant direction of blowing snow; and the percentage of fallen snow relocated by the wind.

These models provide reasonably accurate estimates of climate conditions that are sufficient for the design of living snow fences in New York State in most situations. However, climate variables can be highly localized due to the effects of topography and other site conditions. In some cases, more precise data can be collected in the field using meteorological equipment, such as data logging weather stations, to measure wind speeds, wind direction, precipitation and other weather variables. In addition to the Tabler (2000), an example of how to conduct in-depth climatological analysis for living snow fences is available from Shulski and Seeley (2001).

In-depth climatological studies require large amounts of time and resources; the returns on investment in terms of highly critical data will likely be negligible in most situations. Climate studies in the field are therefore not recommended for most individual living snow fence sites. The methods of Tabler (2000) should be followed instead.

Measure Fetch Distance

Fetch distance (**F**) is an important variable in the analysis of living snow fences. Fetch distance is used in the model of snow transport to determine the quantity of blowing snow at a site in an average year.

- ✓ Using GIS software or field surveying equipment, measure and record the fetch distance in metric units.
- ✓ Starting at the estimated point where the fence will be installed or the edge of the roadway to be protected, measure at a perpendicular angle to the roadway, to the first obstruction upwind that is assumed to disrupt wind patterns and cause snow deposition. Obstructions could include houses, forests or groups of trees. If the predominant winter wind angle is known from climatologic analysis, measure from the fence to the first obstruction at that angle.
- ✓ Take four individual measurements of fetch distance at equidistant spacing across the length of the prospective area where the fence is to be installed
- ✓ Compute the average of the four measurements and round the final value to the nearest meter to calculate the fetch value of the fence.

Estimate The Quantity of Snow Transport at the Site

The primary variable that must be estimated to evaluate a prospective living snow fence site is the average annual snow transport quantity. A summary of how to measure average annual snow transport from Tabler (2000) is provided here. Average annual snow transport quantity (**Q**) can be estimated using the following model:

$$Q = 1500(0.17)(S_{we,AS})(1-0.14^{F/3000})$$

Where:

Q is average annual snow transport quantity in units of t/m (metric tons per linear meter)

(0.17) is the assumed snow relocation coefficient (**C_r**) of snowfall

(**S_{we,AS}**) is the water equivalent of snowfall over the drift accumulation season in meters

F is the fetch distance in meters

Snow transport (**Q**) is measured in units of t/m, or metric tons (1,000 kg) of snow water equivalent per linear meter of fence (or roadway to be protected). The assumed **C_r** value of 0.17 represents a statewide average provided and described by Tabler (2000) as the recommended value for designing snow fences in New York State when a more precise value is not known or measured for the site in question. Snowfall water equivalent over the drift accumulation season (**S_{we,AS}**) in the equation above can be estimated using the following model from Tabler (2000):

$$S_{we,AS} = (-695.4 + 0.076 * \mathbf{Elev} + 17.108 * \mathbf{Lat})(0.10)$$

Where:

S_{we,AS} is water equivalent of snowfall over the drift accumulation season in inches[^]

Elev is the elevation of the snow fence site in meters

Lat is the degrees north latitude of the snow fence site

(0.10) is the assumed water equivalent of snowfall in New York State (Tabler 2000)

*^The output of Equation 2 must be converted from inches into meters to be used in the snow transport (**Q**) model above*

Note that “snowfall over the drift accumulation season” is different from the total annual snowfall for a location, the former being delimited by snowfall that does not contribute to the sustained growth of the snowdrift around the fence (i.e., snow that falls and melts before the drift achieves

sustained growth or snow that falls after the drift has started to permanently melt in the spring). Elevation and latitude values can be measured at the linear center of each fence in Google Earth. The 0.10 value for the water equivalent of snowfall is assumed to be an accurate statewide assumption based on Tabler (2000). If a more precise value at each site is known, substitute it for 0.10 in Equation 2.

Assessing and Measuring Soil Properties

After the site has been preliminarily evaluated remotely and in the field, and the average annual snow transport has been estimated, undertake field samples and analysis of soils. **Soil quality is critical to a living snow fence surviving and growing.** A thorough soil evaluation during site assessment determines if soil quality can support a living snow fence. If soils are determined to be of poor quality, substantial efforts to improve the soils may be required. The critical factors in assessing soil quality are: soil depth, drainage, fertility, percentage of rocks by volume, and soil texture.

- ✓ Begin the soil assessment by evaluating the existing vegetation on the site, to get a rough indication of soil conditions. If the site supports lush woody vegetation or agricultural crops, the soil quality is likely sufficient for a living snow fence. If existing vegetation is sparse or primarily herbaceous (non-woody), this may indicate poor or degraded soils. Soils in or near the right of way may be degraded from previous construction activities. Note the presence of wetland indicator species, such as sensitive fern or cattails on the site, as this may indicate saturated soils and the presence of wetlands that may hinder living snow fence growth and require special permits. Agricultural soils previously used for crops are generally fertile and otherwise sufficient for planting with little modifications. Right of way soils can be heavily degraded or contain high levels of fill. These soils may require high levels of modification to support healthy living snow fences and planting should be approached cautiously.

- ✓ Consult the Natural Resource Conservation Service (NRCS) soil survey maps (websoilsurvey.nrcs.usda.gov) for site-specific information on soil depth, drainage class, fertility and texture. Loams and sandy loams are preferred soils for most species. Soils with high clay content may impede drainage. The best sites for a living snow fence should have an NRCS soil drainage classification of “well drained” to “moderately well drained”. “Poorly drained” and

“somewhat poorly drained” soils will cause stunted growth or mortality in most species and will require more precise plant selection or substantial site modifications to improve drainage.

- ✓ Take soil samples at several locations across the area where the living snow fence will be planted (Figure 5) and have the soil tested by a university lab or environmental engineering firm for: pH, percentage of organic matter, soluble salts, available nitrogen, phosphorus, potassium, calcium, and magnesium. Follow the soil sampling procedures specified by the lab that will do the analysis. For woody plants, sampling the top 6 to 10 inches of soil is the most critical. Evaluate the chemical properties of the soil and consider the need for soil amendments in the design, species selection, site preparation, and installation phases.

- ✓ Dig a soil pit on the prospective installation location at several points across the site to expose the soil profile to a depth of 24 inches. Examine the soil profile in each pit to supplement and confirm NRCS data. Observe and evaluate the soil layers, textures, depths and the percentage of rocks in each layer.
 - If rocks, debris or large roots make up more than 50 percent of the soil volume, the site is likely unsuitable for a snow fence installation without substantial site modifications.
 - Determine the depth to root restricting layer (bedrock, clay, water table, etc.) and make sure there is sufficient depth for proper root development. Depth to restricting layer should be at least 18 inches.
 - Confirm the NRCS soil drainage classification at each soil pit across the site as indicated by the presence of soil mottling. Mottling is indicated by distinctive orange and grey soil particles, both occurring at the same depth in the soil profile. This indicates the depth to a seasonal water table and probable root restricting layer. High-quality sites with adequate drainage will show no signs of mottling at depths of 24 inches or greater. If mottling is observed at depths of 12 inches or less, the site may be too wet and unsuitable for planting. Some tree and shrub species tolerate wet conditions; only a limited number of species suitable for living snow fences thrive and grow rapidly in saturated soils.

- ✓ Consult your local environmental specialist, extension agent, or NRCS staff if you have questions about any of the steps in the soil assessment process.

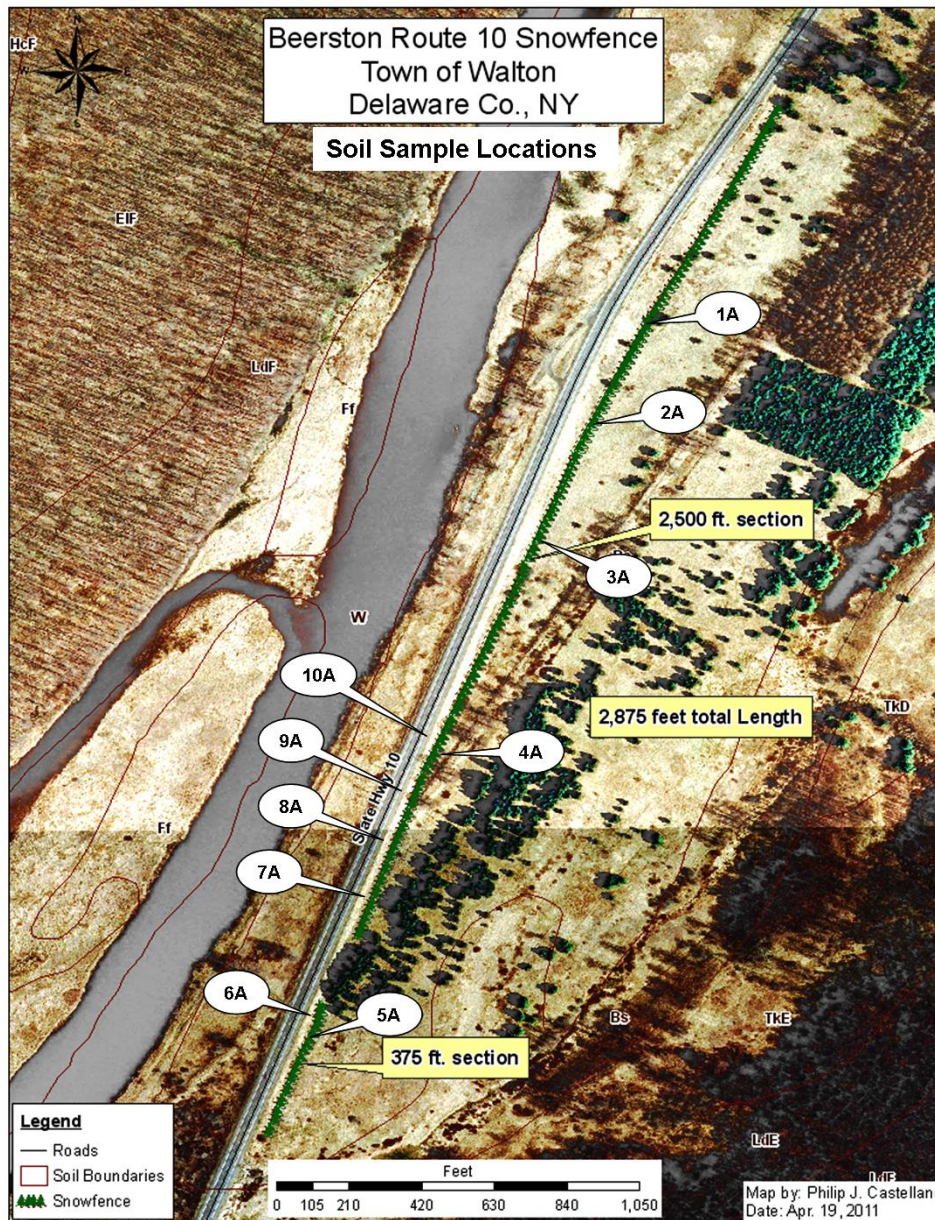


Figure 5: Soil map showing NRCS soil classification boundaries, the approximate location of a prospective living snow fence and soil sample locations and identification tags for soil samples taken at the site to evaluate soil quality and determine the appropriate modifications

Conclusion

The protocols in this document offer a simple methodology for site analysis and measurement of most prospective living snow fence sites to obtain the necessary information for the next steps of living snow fence design, site preparation and installation.

Each living snow fence site and each planting are unique and should be considered and analyzed individually. The protocols can be adjusted as the design team deems appropriate.

If the protocols are followed, the essential data for evaluating a prospective living snow fence site is gathered: identifying the blowing snow problem; examining aerial photos; assessing site challenges and potential solutions; measuring the fetch distance; estimating snow transport; and sampling soil conditions.

References

- Shulski M and Seeley (2001) Climatological characterization of snowfall and snow drift in Minnesota: for the design of living snow fences. Mn/DOT Agreement No.74708. University of Minnesota, Minneapolis, MN http://www.climate.umn.edu/snow_fence/intro.html
- Tabler, R.D. 2000. *Climatological analysis for snow mitigation in New York State*. Tabler and Associates. Niwot, CO.
- Tabler, R.D. 2003. *Controlling blowing and drifting snow with snow fences and road design*. Tabler and Associates. Niwot, CO.

Task 3-B: Pre-installation Site Evaluations

Task 3-B of this project called for site measurements of the four demonstration sites and LSF installations associated with workshops one through eight. This task was completed on a year-by-year basis and results were incorporated directly into classroom and field presentations and the training materials provided in Task-2A and used in Task 2-B. Site measurements encompassed several factors including the length of the road area to be protected by the LSF to be installed, the estimated setback distance required between the road and the fence, the fetch distance or the area upwind of the fence contributing to the blowing snow problem, and estimates of annual blowing snow quantity. Measurements also included soil sampling, laboratory testing and analysis of results to determine the fertility and other chemical and physical properties of the soils on which the LSF would be installed, as well documentation of empirical data from soil pits dug at each site to garner more information. Soils are critically important for the survival and optimal growth of LSF. Fertility, drainage, aeration, texture, organic matter, pH and other factors must all support the selected species or site conditions or be modified to bring conditions within acceptable ranges. Soils on several of the sites were modified with lime, fertilizers, and/or compost as a result of these site measurements and this information and process was shared with workshops participants, stressing the importance of soil health in relation to plant health. Examples of site measurements and soil analysis/modifications conducted throughout this project are included in the guidelines (1-A), training materials (2-A) and protocols (3-A) of this report.

Task 3-C: Protocol for Assessing Living Snow Fence Effectiveness

Task 3-B of this project called for site measurements of the four demonstration sites and LSF installations associated with workshops one through eight. This task was completed on a year-by-year basis and results were incorporated directly into classroom and field presentations and the training materials provided in Task-2A and used in Task 2-B.

Site measurements encompassed several factors including the length of the road to be protected by the LSF to be installed, the estimated setback distance required between the road and the fence, the fetch distance or the area upwind of the fence contributing to the blowing snow problem, and estimates of annual blowing snow quantity.

Other measurements included soil sampling, laboratory testing and analysis of results to determine the fertility and other chemical and physical properties of the soils on which the LSF would be installed, as well documentation of empirical data from soil pits dug at each site to garner more information.

Soils are critically important for the survival and optimal growth of LSF. Fertility, drainage, aeration, texture, organic matter, pH and other factors must all support the selected species or site conditions or be modified to bring conditions within acceptable ranges. Soils on several of the sites were modified with lime, fertilizers or compost as a result of these site measurements and this information and process was shared with workshop participants, stressing the importance of soil health in relation to plant health. Examples of site measurements and soil analysis/modifications conducted throughout this project are included in the guidelines (Task 1-A), training materials (Task 2-A) and protocols (Task 3-A) of this report.

Research Project C-06-09

Designing, Developing and Implementing a Living Snow Fence Program for New York State

Task 3-C, 3-C1 & 3C2

Protocol for Field Measurements of Effectiveness of Operationally Mature Living Snow Fences

August, 2013



State University of New York
College of Environmental Science and Forestry



New York State
Department of Transportation

Justin P. Heavey

Dr. Timothy Volk

Dr. Lawrence Abrahamson

State University of New York
College of Environmental Science & Forestry

John Rowen

New York State Department of Transportation

Background

The structure of living snow fences, and the manner in which they hold snow, change over time as plants grow. This document provides protocols for a complete assessment of living snow fence structure and function that can be applied at any point during the life cycle of a living snow fence. The two primary vegetation characteristics affecting the snow trapping function of living snow fences are the fence height (**H**) and optical porosity (**P**). Height and porosity combine to create the snow storage capacity of the fence (**Q_c**). Vegetation characteristics are measured in the field to estimate the level of functionality of living snow fences. Site characteristics that influence the quantity of annual snow transport (**Q**), such as the fetch distance (**F**), can be measured in the field with surveying equipment or measured remotely using a geographic information system (GIS). Vegetation and site characteristics can then be modeled using the snow fence equations developed by R. Tabler (2000 and 2003) to determine the snow trapping function of the fence.

Tabler's models of snow trapping function are formulated using metric units. To use the models, data must be collected in, or converted to, metric units. Estimates of snow trapping function can be verified using the protocol provided in this document for measuring snow depth and density.

Undertaking winter field measurements raises safety issues because of the season and because snow and ice work by transportation agencies may limit access to the right of way. Before making a field visit, the user of this protocol must contact the agency maintaining the highway to ensure it is safe to work on the roadside.

1. Examine Aerial Photos of the Snow Fence Site

Examining aerial photos of a living snow fence and the surrounding land assists in field measurement by providing an overview of the site and context of the landscape around the fence, including the area *upwind* of the fence that contributes to the blowing snow problem known as the fetch distance. The distance from the *downwind* edge of the fence to the edge of the roadway is known as the setback distance. Looking at aerial photos before a field visit can help in determining the best parking and access route to the fence for field measurements. Aerial photos provide a bird's eye view of the site. They can show things that may not be readily visible from the ground but may be important to the analysis of the snow fence and site. An example of an aerial photo of a living snow fence site is provided in Figure 1.



Figure 1: Aerial photo of a living snow fence site from Google Earth software. The living snow fence is the row of dark green vegetation indicated by the tree icon, located on New York Route 167, Town of Manheim, Herkimer County.

The Google Earth software program is a free, user-friendly GIS program that often has the most up-to-date aerial photos. Living snow fence sites can be easily viewed from multiple angles and resolutions in this software and site locations can be “bookmarked” for easy identification and further analysis. Distances and elevations can also be quickly and easily measured in Google Earth and shapes can be marked on the landscape and printed as aerial maps that can assist in the next steps of evaluating living snow fence structure and function. Examining aerial photos of living snow fences also helps to frame the snow fence in the context of the important site characteristics that contribute to the blowing snow problem. A diagram illustrating the basic elements of a snow fence site is provided in Figure 2. From top to bottom, this diagram shows the following:

- A row of houses that indicates an obstruction to the wind where snow transport is assumed to start
- The fetch distance, that is the open area upwind where snow is lifted off the ground and transported by the wind toward the fence,
- The living snow fence which disrupts the wind and causes snow deposition around the fence,
- The setback distance between the roadway and the fence, and the roadway protected by the fence.

Note that a 100-meter sampling plot and a minimum 7.5-meter buffer on either side of the fence is included in this diagram and explained in the next step, “Establishing a Sampling Plot”.

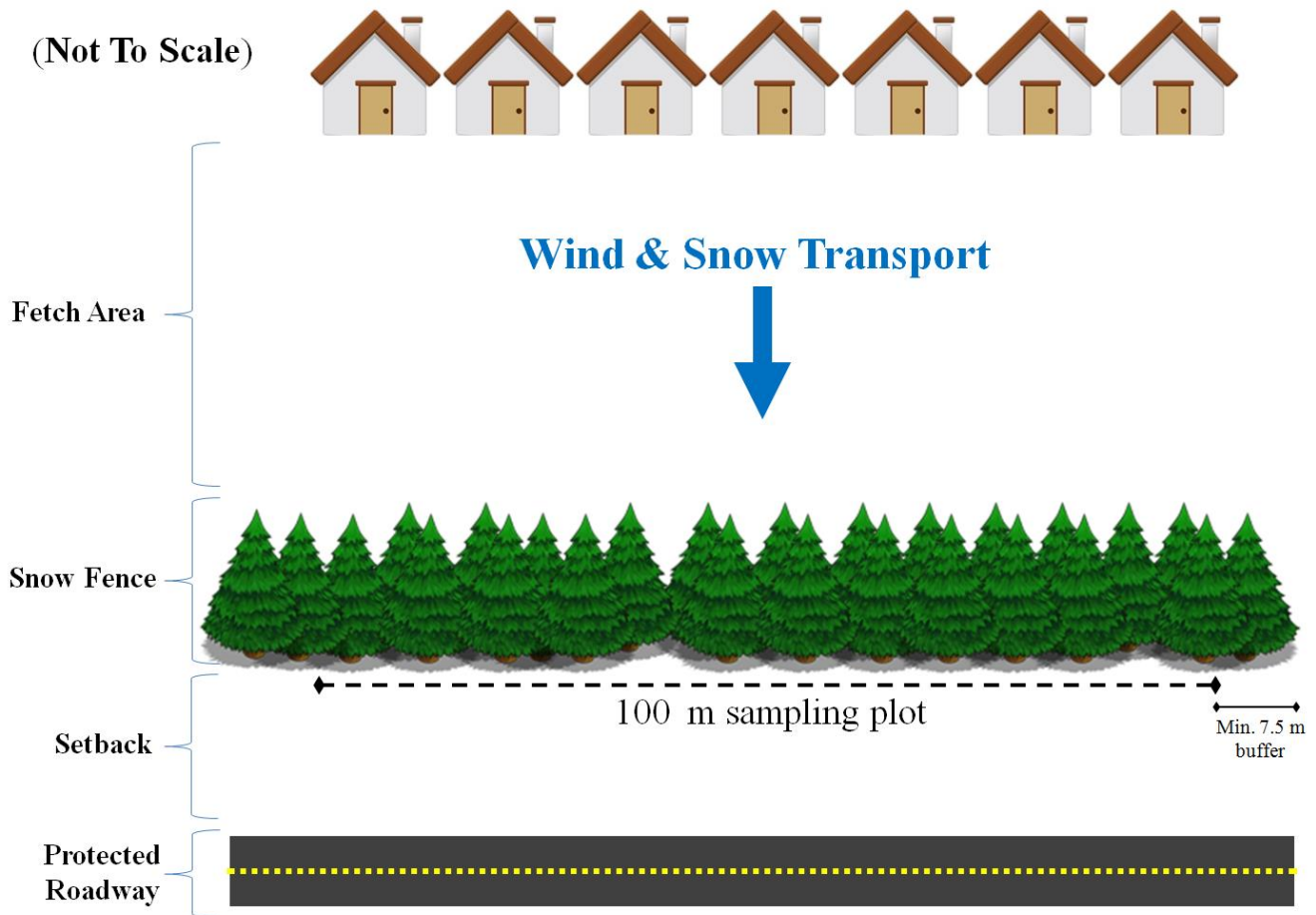


Figure 2: Diagram of living snow fence site showing the basic elements that influence snow control

2. Establish a Sampling Plot

Living snow fences vary in length and can be several hundred meters/feet long or more. For fences up to 100 meters long, it should be possible to take measurements along the full length of the fence. For fences over 100 meters long, it is useful to establish a sampling plot or plots across a portion of the fence and take all measurements within the sampling plot/plots. Living snow fences of consistent age, species makeup, planting pattern, soil conditions and management practices across the entire length

of the fence generally will grow to a height and porosity that is relatively consistent from end to end. Measurements taken within a sampling plot of a living snow fence of relatively consistent growth characterize a subsection of the entire fence that is representative of the entire fence, just as a biological study samples a subset of a population to determine the structure of the larger population.

For living snow fences of up to 300 meters, one sampling plot, approximately 100 meters (328 feet) in length, established across the linear center of a fence, will be sufficient. For very long fences 300 meters or longer, one or more additional sampling plots can be established along the length of the fence at equidistant spacing. Multiple plots should be approximately equal in length and long enough (generally between 50 and 100 meters) to collectively total approximately one-third of the total fence length. The measurements of each plot can be averaged together for a final value of each structural variable of the fence. Sampling plots can be measured and marked on aerial photos by remotely using GIS, then established in the field using an aerial map printout. Alternatively, sampling plots can be established in the field using field surveying and measuring equipment. Sampling plots should be established with at least 7.5 meters (25 feet) on either side of the plot to provide a buffer against “edge-effects” where the structure and function of the fence may differ due to aerodynamic effects that are created by wind at the end of the fence.

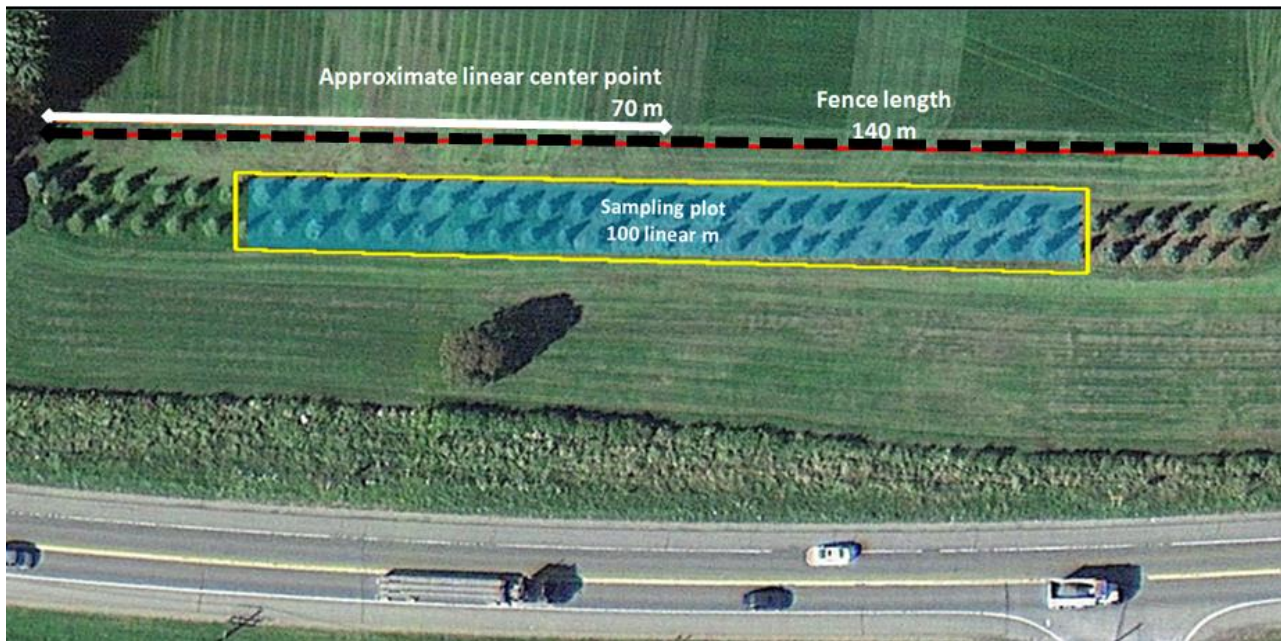


Figure 3: Aerial photo of a living snow fence from geographic information software showing the measurement of fence length, linear center point and 100-meter sampling plot established around the center point. This snow fence is on New York Route 60 in the town of Pomfret, Chautauqua County.

Protocol for Establishing a Sampling Plot

- A. Using GIS software or field surveying equipment, measure and record the total fence length in meters (Figure 3).
- B. If the total fence length is between 100 and 300 meters, determine the linear center point of the fence and establish a 100-meter sampling plot around the center of the fence.
- C. If the total fence length is greater than 300 meters, divide the length by 3. That is the total length to be tested in multiple plots. Divide this length into two or more plots of equal size, each a minimum of 50 meters and a maximum of 100 meters long. Divide the total length of the fence into the number of equal-length segments needed to locate the center point of the required number of sample plots and establish a sampling plot around the center of each point.
- D. Mark the beginning, center and end of the sampling plot with flagging tape tied to the fence vegetation, stakes or other appropriate marking techniques

3. Measure Setback Distance

The length of setback distance is an important variable in the function of snow fences. Setback should be large enough to accommodate the entire length of the downwind drift, but not so large that the wind regains speed and creates snow transport between the fence and the roadway. Measure setback distance by following the steps below and refer to Figure 4.

*Note: The protocol below is a methodology for measuring the setback distance on existing living snow fences, not for calculating an appropriate setback distance for the design of new living snow fences.

Protocol for Measuring Setback

- A. Using GIS software or field surveying equipment, measure and record the setback distance in units of meters as follows.
- B. Measure the distance from the fence vegetation, at the angle of the prevailing wind, to the edge of roadway pavement.
- C. Take four measurements of setback distance within the established 100-meter sampling (or within each sampling area of multiple-plot fence) at approximately equidistant spacing as shown in Figure 4.
- D. Compute the average of all measurements and round the final value to the nearest meter to calculate the setback distance value of the fence.

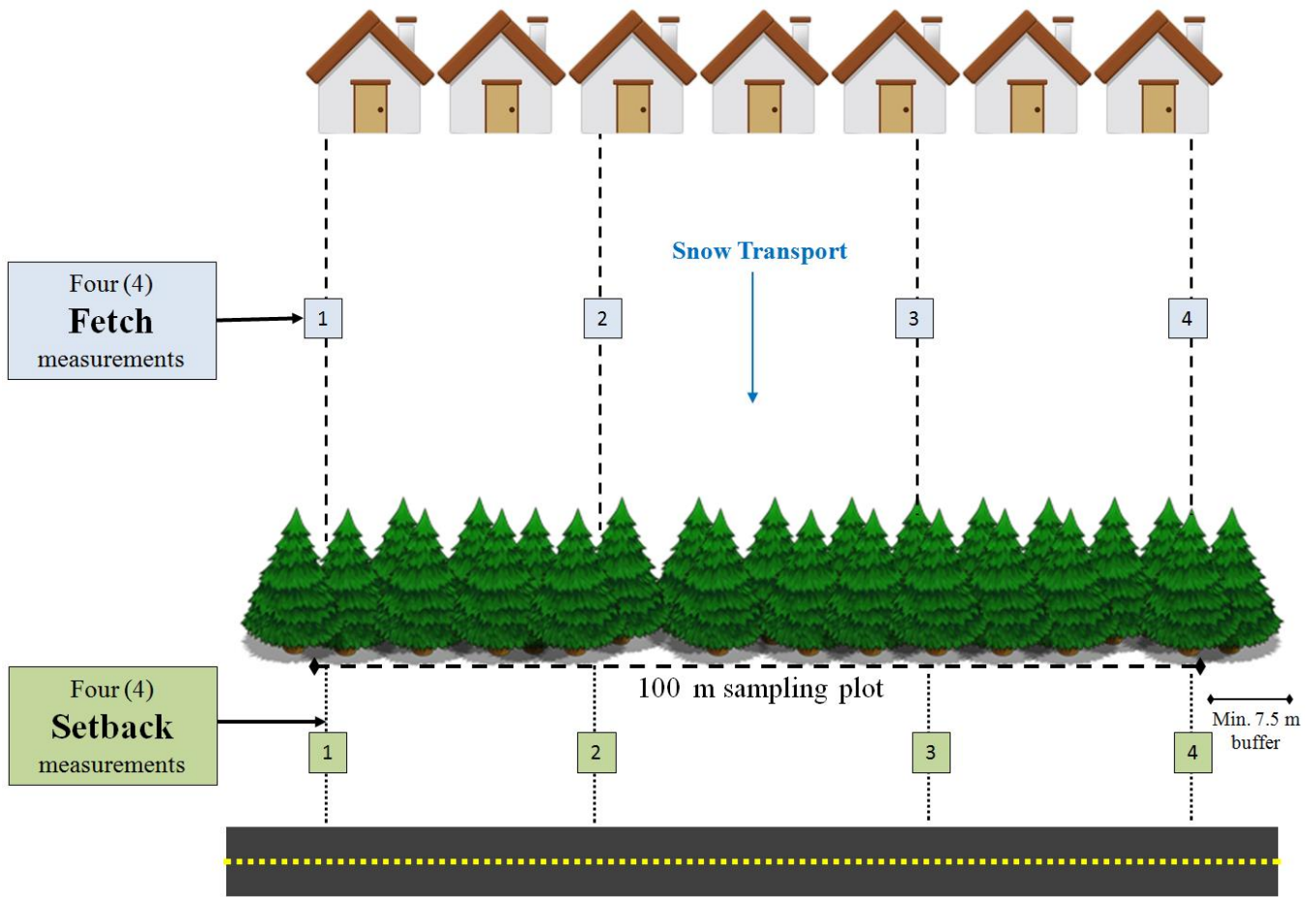


Figure 4: Sampling diagram for measuring setback distance and fetch distance, as described in Steps 3 and 4

4. Measure Fetch Distance

Fetch distance is an important variable in the analysis of living snow fences. Fetch distance is used in the model of snow transport to determine the quantity of blowing snow at a site in an average year.

Protocol for Measuring Fetch Distance

- A. Using GIS software or field surveying equipment, measure and record the fetch distance in units of meters as follows.
- B. If the predominant winter wind angle is not known, start at the fence vegetation and measure at a perpendicular angle to the first obstruction upwind that is assumed to disrupt wind patterns and to cause snow deposition such as houses, forests or groups of trees. If the predominant winter wind angle is known from climatologic analysis, measure from the fence to the first obstruction at that angle.
- C. Take four measurements of fetch distance within the established 100-meter sampling at approximately equidistant spacing, as shown in Figure 4.
- D. Compute the average of the four measurements and round the final value to the nearest meter to calculate the fetch value of the fence.

5. Measure Fence Height

Height (**H**) of living snow fences is measured with a telescoping height pole as follows, a range finder (such as a Nikon Forestry Pro) or other device. Two people will make height measurements easier, with one person to operate the height pole and call out measurements, and one to record the height values and to act as a spotter to align the top of the pole with fence, if needed.

Protocol for Measuring Fence Height

- A. In the field, measure the fence height within the sampling plot(s).
- B. Note: if using a height pole, place it on level ground at the base of the fence vegetation, as close to the stool/stump (for shrubs) or main stem (for trees) as possible. Hold the pole at a perpendicular angle to the ground and extend the pole until it is even with the height on the

vegetation where the vegetation is acting as a continuous, uniform fence. Record the height of the fence, then lower the pole to a height where it can be moved to the next measurement.

- C. Take equidistant measurements across the length of each sampling plot at approximately 12.5 meters (e.g. eight measurements for a 100-meter sampling plot as shown in Figure 5).
- D. Compute the average of all measurements and round the final value to the nearest meter to calculate the height value of the fence

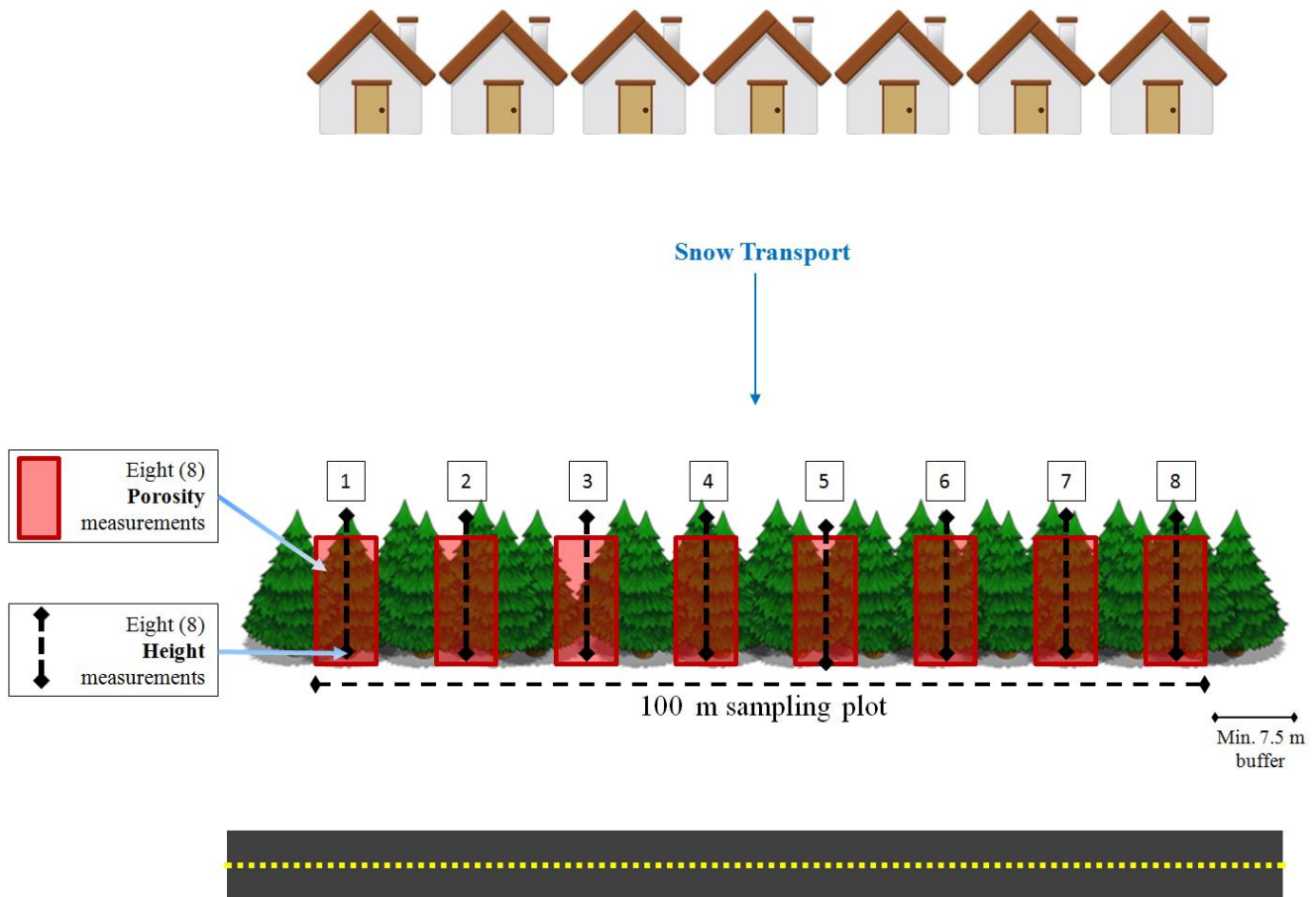


Figure 5: Sampling diagram showing height and porosity measurements for living snow fence 100 meter sampling plots shown and as described in Steps 5 and 6.

6. Measure Fence Optical Porosity

Optical porosity (P) is an important characteristic of living snow fences that influences the snow storage capacity of the fence and the length of the downwind drift. The porosity of a fence is the percentage of

visible open space not occupied by vegetation when the fence is viewed at a perpendicular angle in winter (after leaf fall). The percent porosity of a fence is the inverse of the vegetation density. For example, a fence with 75 percent porosity has a 25 percent density and has more open (porous space) than space that has filled in with vegetation. A fence with 50 percent porosity is half open and half closed by vegetation and provides the highest amount of storage capacity. Two protocols for measuring optical porosity of living snow fences are provided here, based on two primary vegetation types of living snow fences: shrubs and evergreen trees.

Protocol for Measuring Fence Porosity Using the Chroma-key Backdrop Technique (shrubs)

- A. Use a backdrop at least 1 meter wide by 3 (three feet by nine feet) meters tall for a sufficiently large sample of porosity. The backdrop should be made of a synthetic fabric, such as “weblon,” that is durable, opaque, smooth and red in color. A red backdrop provides a distinct and consistent color contrast between fence vegetation and porous (open) space in the fence. The backdrop should be collapsible for transporting and framed with sturdy aluminum or wooden pole, so the backdrop can be stretched flat by one or two people. An example of a suitable chroma-key backdrop held in front of a shrub-willow living snow fences is provided in Figure 6.
- B. Hold the backdrop perpendicular to the ground, as close to the vegetation as possible. Photograph the backdrop from the opposite side of the fence (with the fence vegetation between the camera and the backdrop), at a distance of approximately 2.5 meters downwind, or at whatever distance is necessary to capture the entire backdrop area with as little space on the top and bottom of the backdrop in the photo as possible. Use the highest resolution setting on the camera and the “auto mode” setting if you are not familiar with advanced digital photography techniques.
- C. Repeat Step B at equidistant locations along the length of the sampling plot(s), at the same locations where the height measurements were taken (e.g. eight measurements for a 100 meter sampling plot, as shown in Figure 5).



Figure 6: Chroma-key backdrop held in front of a shrub-willow living snow fence to create a contrast between fence vegetation and open space to photograph the fence and to measure the optical porosity

Protocol for Measuring Fence Porosity Using the High-Contrast Technique (evergreen trees)

If the fence cannot be accurately measured using the chroma-key backdrop technique due to large height, large widths and/or low porosities, as is often the case with mature evergreen fences, proceed with the high-contrast technique as follows.

- A. Photograph the fence at a distance of approximately 2.5 meters upwind or downwind at a perpendicular angle. If possible, try to photograph the fence in the early morning or late evening when the fence can be photographed with the sun behind one side. This increases light infiltration through the open space (porosity) of the fence and improves the contrast between porous space and vegetation. If possible, increase the contrast setting on the camera to further accentuate the open space versus vegetation. The photo contrast can also be increased in the next step of processing the photos with photo editing software. An example of a photo taken on an evergreen living snow fence is provided in Figure 7. When comparing the optical porosity results with other fences that were sampled using the chroma-key technique, it is advisable to photograph approximately the same size area that appears in front of the backdrop. Otherwise, a larger area of fence can be captured. In either case, one complete replication of the planting pattern of the fence should be captured in the photo(s) if possible. For example, if the fence is planted in a double off-set row pattern with Norway

spruce in the front row and white spruce in back row, capture the entirety of both rows (front row and back row) in one photo, or in multiple side-by-side photos.

- B. Repeat step B eight times at equidistant locations along the length of the 100-meter sampling plot as shown in Figure 5, at the same locations that the height measurements were taken.



Figure 7: Photographic sample of optical porosity of an evergreen living snow fence using the high contrast technique

Protocol for Processing Porosity Photos from the Chroma-key and High-Contrast Techniques

After photos have been taken in the field, they must be processed to determine the optical porosity. Use a photo editing software program to accomplish this as outlined in the steps below.

- A. Begin by opening a copy of the first photo to be processed in the photo editing program and maximize the program and the picture window to occupy the entire computer screen
- B. If necessary, rotate the image so it is right side up (as it would appear naturally)
- C. Repeat step B to maximize the photo on screen again if necessary
- D. Carefully crop around the red backdrop area or the desired sample area. Capture as much of the red area (or sample) as possible. The remaining area after the crop should contain only red backdrop (or sample area) and vegetation
- E. Repeat step B to maximize the photo on screen again if necessary

- F. Use the “magic wand” or equivalent selection tool to select to the red or open area (the porosity) in the photo
- G. Clear the selected area to verify an accurate selection and confirm that there is very little or no red (or background color) left in the picture and none of the vegetation has been cleared. It may be necessary to zoom in on the image to verify that small stems or edges of the stems have not been cleared. If necessary, redo step F with different settings. Several attempts and adjustments may be necessary to accurately clear all open space without clearing any vegetation. It is important to precisely clear all the open space and no vegetation to get an accurate measurement.
- H. Once the open space in the photo has been cleared successfully, use the selection to tool to select all the open space that has been cleared, making sure all the white space is selected and none of the stems are selected. The total white space represents the optical porosity.
- I. Use the histogram or equivalent tool to count the number of cleared white “pixels” shown in the histogram window in a corresponding data sheet in a column labeled “blank pixels.”
- J. Select the entire cropped photo and use the histogram tool to count the total pixels in the image, then enter this number in the corresponding data sheet in a second column labeled “total pixels”
- K. Dividing the value in the “blank pixels” column by the value in the “total pixels” column in the data sheet gives the optical porosity that can be expressed as a decimal or percent
- L. Save the photo file as a copy to retain the original unprocessed image
- M. Repeat steps “A” through “L” for each of the porosity photos taken at each site. Average all porosity photos together to calculate the final optical porosity value of the snow fence.

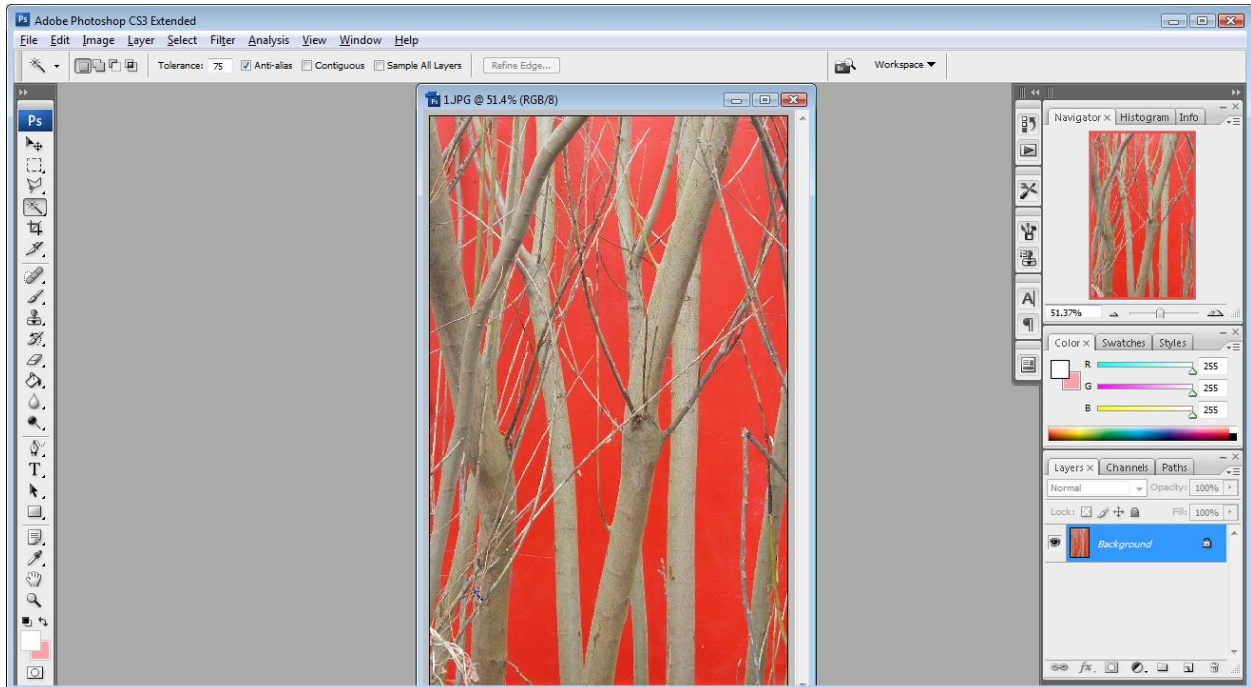


Figure 8: Example of a cropped photo in photo editing software

7. Estimate The Snow Trapping Function

Average Annual Snow Transport (Q)

Snow transport (**Q**) can be estimated using the following model from Tabler's (2000) report *Climatologic Analysis for Snow Mitigation in New York State*:

$$Q = 1500(0.17)(S_{we,AS})(1-0.14^F/3000)$$

Equation 1

Where:

Q is average annual snow transport quantity in units of t/m (metric tons per linear meter)

(0.17) is the assumed snow relocation coefficient (**C_r**) of snowfall

(**S_{we,AS}**) is the water equivalent of snowfall over the drift accumulation season in meters

F is the fetch distance in meters

The assumed **C_r** value of 0.17 represents a statewide average provided and described by Tabler (2000) as the recommended value for designing snow fences in New York State when a more precise value is not known or measured for the site in question. A more precise value for the snow fence site can be used for the **C_r** value if known. Snow transport (**Q**) and snow fence capacity (**Q_c**) are measured in units of t/m, or metric tons of snow water equivalent (SWE) per linear meter of fence

Snowfall water equivalent over the drift accumulation season ($S_{we,AS}$) in the above model (Equation 1) can be estimated using the following model from Tabler (2000):

$$S_{we,AS} = (-695.4 + 0.076 * \mathbf{Elev} + 17.108 * \mathbf{Lat})(0.10)$$

Equation 2

Where:

$S_{we,AS}$ is the water equivalent of snowfall over the drift accumulation season in inches[^]

\mathbf{Elev} is the elevation of the snow fence site in meters

\mathbf{Lat} is the degrees north latitude of the snow fence site

(0.10) is the assumed water equivalent of snowfall in New York State (Tabler 2000)

Note: The output of Equation 2 must be converted from inches into meters to be used in Equation 1.

Note that “snowfall over the drift accumulation season” is different from the total annual snowfall for a location. The former is/includes being delimited by snowfall that does not contribute to the sustained growth of the snow drift around the fence (i.e., snow that falls and melts before the drift achieves sustained growth or snow that falls after the drift has started to permanently melt in the spring). Elevation and latitude values can be measured at the linear center of each fence in Google Earth. The 0.10 value for the water equivalent of snowfall is assumed to be an accurate statewide assumption based on Tabler (2000). If a more precise value at each site is known, it can be substituted for 0.10 in Equation 2.

Snow Storage Capacity (Q_c)

Snow storage capacity (Q_c) of the snow fence can be estimated using the observed height and porosity values from each fence and the following model from Tabler (2003):

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

Equation 3

Where:

Q_c is the snow storage capacity of the fence in units of t/m (metric tons per linear meter)

P is the observed optical porosity value of the fence

H is the observed height of the fence in meters

8. Measure the shape and quantity of the snowdrift

The quantity of snow in the snowdrift around a living snow fence can be measured using the following protocol: Snowdrifts can be measured at the end of a drift accumulation season in the late winter or early spring or over the course of a snow season. The quantity and shape of a snow drift around a living snow fence is estimated by probing and measuring the snow depth and density of snow pack around the fence. Four transects that extend upwind and downwind of the fence are established and measurements are taken along each transect (Figure 9). The mean snow depth along the four transects is calculated to determine the average cross-sectional profile of the drift across the length of the fence (Figure 10). Once the cross-sectional profile of the drift has been measured, the

quantity of snow deposition can be estimated by calculating the area of the drift and multiplying the area by the measured snow density.

Appendix A is a worksheet that can be taken out to the field to tally snowdrift measures.

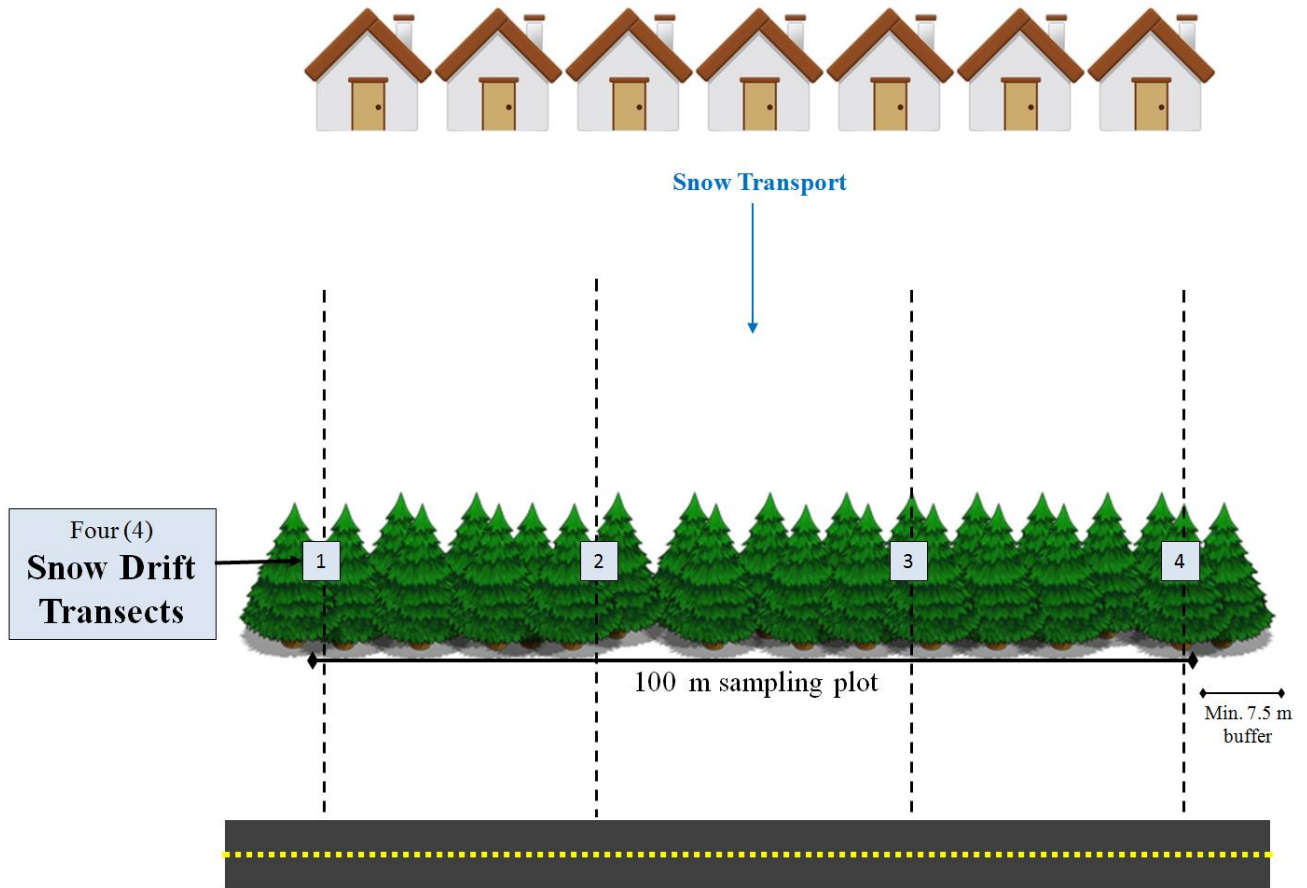


Figure 9: Sampling diagram showing four transects established at equidistant spacing across the 100-meter sampling plot for measuring snow depth and density as described in Step 8.

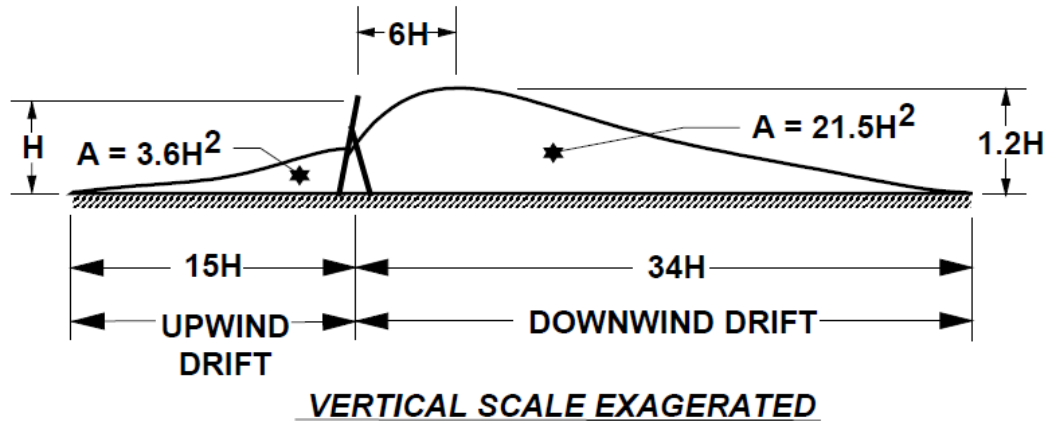


Figure 10: Diagram illustrating the cross-sectional profile of an equilibrium (full-capacity) snowdrift around a 50 percent porous structural snow fence. (Diagram from Tabler 2003)

Protocol for Establishing Transects and Measuring Snow Depth and Density

- A. At the beginning of the 100 meter sampling plot, establish the first transect on the downwind side of the fence by staking a metric tape measure into the snow at the base of the fence. Suspend the tape above the highest point of snow drift if possible to get the most accurate measurements, or lay the tape on top of the snow surface.
- B. Extend the tape at a perpendicular angle from the fence to the near edge of the roadway, or until the snow depth is negligible. In general, snow depths less than 0.10 meter can be considered negligible.
- C. Use a specialized snow depth probe, or other measuring stick capable measuring snow drift depths, to measure the snow depth at a series of intervals along the transect, such as 1 meter, 2 meters, 3 meters and so on.

The majority of snow deposition and slope of the drift will likely occur in close proximity to the fence. It is, therefore, logical to space measurements closer together while probing in close proximity to the fence, and space measurements more widely as you move away from the fence. For example, measure the depth every one meter over the first 10 meters of the transect, every two meters from 12 through 20 meters of the transect and every five meters thereafter (Table 1). Record each measurement, and the distance from the fence each measurement was recorded at on a spreadsheet, such as the one provided in the Table 1 on the last page of this document. Repeat steps A through B on the upwind of the fence at a perpendicular angle to the fence, in alignment with the downwind transect.

- D. Now sample snow density on the upwind side of Transect 1 using a metric federal (mount rose) snow tube. Begin by taking a core of the snow at a distance of one meter upwind by inserting the cutting end of the tube directly down into the snowdrift. Turn the tube one half turn and pull the tube up and examine the bottom of the tube for dirt or grass. There should be some dirt or grass on the end of the tube to indicate that the bottom of the tube reached the ground. Wipe off all dirt and grass from the tube.

- E. Record the depth of the snow core at the distance from the fence that it was sampled.
- F. Weigh the snow core with the mount rose scale and cradle and record the mass of the core plus the tube. Later, when calculations are performed, the percent density of the snow water equivalent is determined by dividing the weight of the snow core (minus the weight of the snow tube) by the snow depth.
- G. Repeat steps D through F at 3-5 locations on the downwind side of the fence and three to five locations on the upwind side of the fence along transect 1. Density measurements can generally be taken less frequently and at larger spacing than depth measurements, such as 1, 3, 5, 10, and 20 meters from the fence (Table 1). Larger drifts with steeper slopes may require more than five density samples on each side of transect 1 to accurately characterize average density of the drift or changes in density at different snow depths. Refer to the National Resources Conservation Services (NRCS) Snow Survey Sampling Guide for more detailed instructions on how to sample snow density using a mount rose tube <http://www.wcc.nrcs.usda.gov/factpub/ah169/ah169.htm>
- H. Repeat steps A through C to sample the snow depth profile for each of the remaining three transects. Be sure to make the distances from the fence at which measurements are taken as consistent as possible at each transect. For example if you measure snow depth at 1, 3, and 9 meters on transect 1, measure depth at 1, 3 and 9 meters - - or as close as possible to these intervals - - on all the other transects.

9. Calculate the shape and water equivalent of the drift

After measuring snow depths and density in the field, calculate the cross-sectional profile of the drift and water equivalent of snow as follows.

Protocol for Calculating the Drift Profile and Quantity of Snow Water Equivalent

- A. Enter the snow depths distances from the fence at which each measurement was taken into a spreadsheet. Calculate the mean depth at each distance from the fence by averaging the four measurements from the four transects at each distance. For example, average the recorded snow depth at 5 meters downwind from the fence on transects 1 through 4 to calculate the mean snow depth across the snow fence 5 meters downwind from the fence.
- B. Create a cross-sectional profile of the drift by inputting the mean depths across the four transects into one column and the distance from the fence in another column, with the upwind distances as negative numbers and the downwind distances as positive number (Table 1). Create a dotted line plot from the two columns with the distance from the fence plotted on the X-axis and snow depth plotted on the Y-axis as shown in Figure 11.
- C. Estimate the cross-sectional area of the drift by overlaying triangles or other geometric shapes for which the sides and areas can be easily calculated as show in Figure 12. In most cases, two right triangles will sufficiently encompass the area of the upwind and downwind drift, based on

standard drift geometry dictated by the aerodynamics and deposition patterns of wind transported snow particles encountering a porous barrier (i.e. snow fence). In some cases, the drift may need to be broken up into smaller sections when overlaying shapes to determine the area, such as irregularly shaped drifts or large drifts in which the density of snow varied substantially across the length of the drift. Alternately, a calculus function can be created to calculate the area under the curve based on the slope of the drift profile.

- D. Calculate the average density of snow in the fence using the snow core data. Calculate the snow water content in each sample by subtracting the known mass of the empty snow tube from the measured mass of the core. Divide the water content by the measured depth of the core to give the snow density at each sampling point. If density varies less than 10 percent across all measurements, all density measurements can be averaged and one value can be used for the mean density value of the entire fence. If the variation is greater than 10 percent, analysis of the fence should be broken down into sections, using the average of two consecutive density measurements along a transect as the average density for the snow area in between those two points.

- E. Once the cross-sectional area and the average snow density of the fence is determined, calculate the snow water equivalent (SWE) of the drift by multiplying the area by the percent density. This will give the square meters of m^2 of snow water equivalent in the drift. If the cross-sectional profile is theoretically expanded to one linear meter of fence, the value of snow water equivalent does not change, but the unit of snow water equivalent becomes cubic meters m^3 . One cubic meter of water has a mass of 1000 kg in mass, or one metric ton. Therefore, the value of cubic meters of snow water equivalent is synonymous with the standard unit of snow fence transport and capacity of t/m (metric tons of snow water equivalent per linear meter of fence). This provides an observed value of snow *deposition* around the fence in units of tons per meter, than compared with the estimated values of snow fence capacity (Q_c) and average annual snow transport (Q)

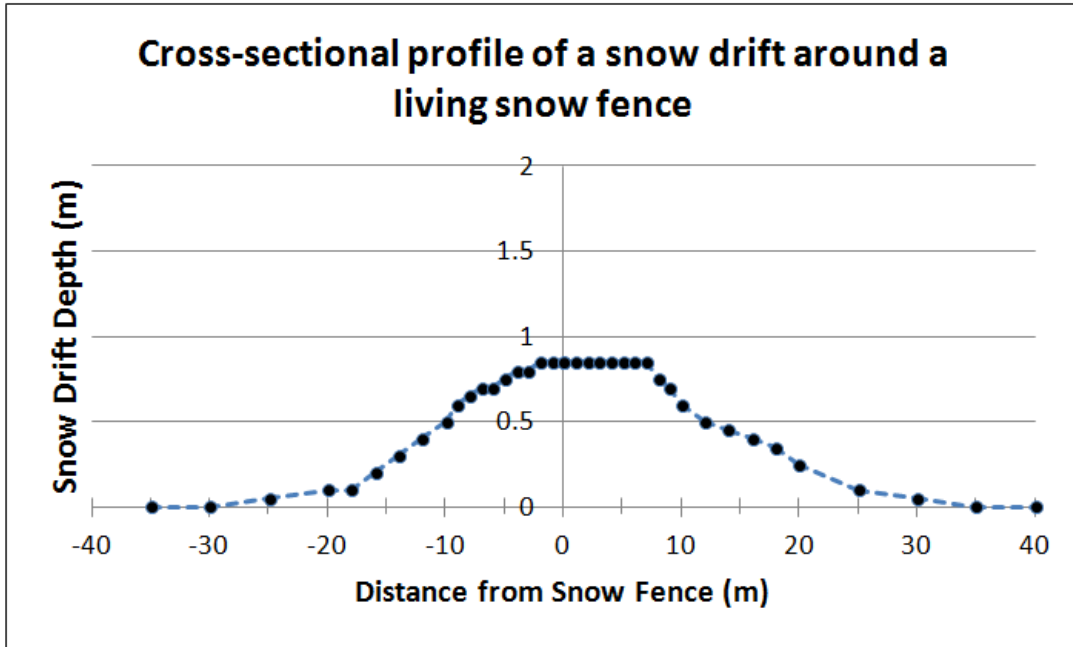


Figure 11: Cross-sectional drift profile of a living snow fence created from mean snow depths measured along four transects upwind and downwind of the fence

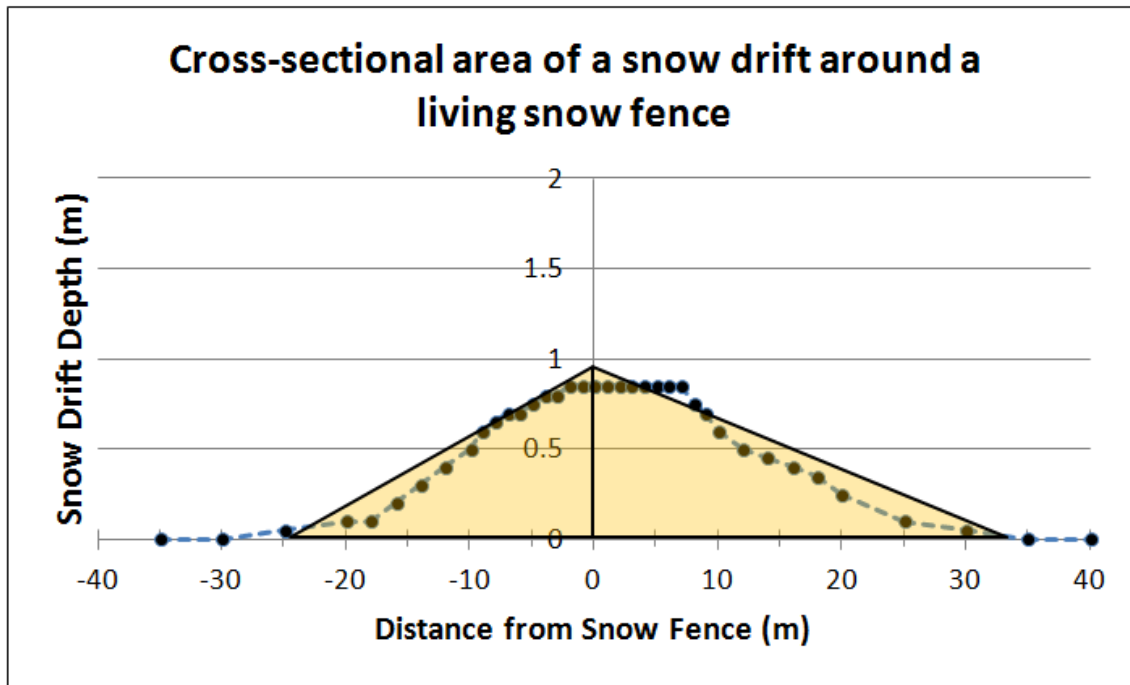


Figure 12: Simple geometric shapes transposed over the plotted drift profile to estimate the area

Conclusion

The preceding protocols can be followed to conduct a thorough analysis of living snow fences of any age and species. Geographic information systems are useful in the preliminary analysis of living snow fences to: examine aerial photos of the site; measure site characteristics, such as fetch and setback distances; and create site maps that can assist in establishing measurement plots and field data collection. Establishing a sampling plot creates a subsection representing the entire fence that can be more easily sampled. The key variables of fence height (**H**) and optical porosity (**P**) can be accurately sampled through measurements within the sampling plot. These variables can be modeled, along with measurements or assumptions of climatic variables, to estimate the snow-trapping function of fences using the models of Tabler (2000, 2003). Key functional variables are the average annual snow transport at the site (**Q**) and the snow storage capacity of the fence (**Q_e**). Estimates of these models can be validated with empirical data collected on snowdrifts and analyzed with the protocols above. In aggregate these protocols provide a complete methodology for measuring, modeling and validating the structure and function of living snow fences.

References

Tabler, R.D. 2000. *Climatological analysis for snow mitigation in New York State*. Tabler and Associates. Niwot, CO.

Tabler, R.D. 2003. *Controlling blowing and drifting snow with snow fences and road design*. Tabler and Associates. Niwot, CO.

Transect 1				Transect 2		Transect 3		Transect 4	
Distance from Fence	Snow Depth	Snow Core Depth	Snow Core Mass	Distance from Fence	Snow Depth	Distance from Fence	Snow Depth	Distance from Fence	Snow Depth
(m)	(m)	(m)	(kg)	(m)	(m)	(m)	(m)	(m)	(m)
-40				-40		-40		-40	
-35				-35		-35		-35	
-30				-30		-30		-30	
-25				-25		-25		-25	
-20				-20		-20		-20	
-18				-18		-18		-18	
-16				-16		-16		-16	
-14				-14		-14		-14	
-12				-12		-12		-12	
-10				-10		-10		-10	
-9				-9		-9		-9	
-8				-8		-8		-8	
-7				-7		-7		-7	
-6				-6		-6		-6	
-5				-5		-5		-5	
-4				-4		-4		-4	
-3				-3		-3		-3	
-2				-2		-2		-2	
-1				-1		-1		-1	

Upwind Snow Drift →



1				1		1		1	
2				2		2		2	
3				3		3		3	
4				4		4		4	
5				5		5		5	
6				6		6		6	
7				7		7		7	
8				8		8		8	
9				9		9		9	
10				10		10		10	
12				12		12		12	
14				14		14		14	
16				16		16		16	
18				18		18		18	
20				20		20		20	
25				25		25		25	
30				30		30		30	
35				35		35		35	
40				40		40		40	

Downwind Snow Drift →

Transect 1				Transect 2		Transect 3		Transect 4	
Distance from Fence	Snow Depth	Snow Core Depth	Snow Core Mass	Distance from Fence	Snow Depth	Distance from Fence	Snow Depth	Distance from Fence	Snow Depth
(ft)	(ft)	(ft)	(lb)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)
-130				-130		-130		-130	
-110				-110		-110		-110	
-90				-90		-90		-90	
-80				-80		-80		-80	
-70				-70		-70		-70	
-60				-60		-60		-60	
-50				-50		-50		-50	
-45				-45		-45		-45	
-40				-40		-40		-40	
-35				-35		-35		-35	
-30				-30		-30		-30	
-25				-25		-25		-25	
-21				-21		-21		-21	
-18				-18		-18		-18	
-15				-15		-15		-15	
-12				-12		-12		-12	
-9				-9		-9		-9	
-6				-6		-6		-6	
-3				-3		-3		-3	

Upwind Snow Drift →



3				3		3		3	
6				6		6		6	
9				9		9		9	
12				12		12		12	
15				15		15		15	
18				18		18		18	
21				21		21		21	
25				25		25		25	
30				30		30		30	
35				35		35		35	
40				40		40		40	
45				45		45		45	
50				50		50		50	
60				60		60		60	
70				70		70		70	
80				80		80		80	
90				90		90		90	
110				110		110		110	
130				130		130		130	

Downwind Snow Drift →

Note: All English measurements must be converted into metric units before applying snow load equations. It is recommended that all measurements be taken in metric units whenever possible.

Tasks 3-D and 3-E: Field Measurements and Key Factors of Operationally Mature Fences

Research Project C-06-09

Designing, Developing, and Implementing a Living Snow Fence Program for New
York State

Tasks 3-D, 3-D1, 3-D2, 3-D3, 3-E, 3-E1, 3-E2, 3-E3

**Field Measurements and Analysis of
Effectiveness of Operationally-Mature Snow
Fence Vegetation in New York State**

August, 2013



State University of New York
College of Environmental Science and Forestry



New York State
Department of Transportation

Justin P. Heavey
Dr. Timothy Volk

State University of New York
College of Environmental Science & Forestry

John Rowen

New York State Department of Transportation

Background

Task 3-D of research project C-06-09 calls for the collection of effectiveness data on living snow fences using the protocols developed in Task 3-C of this project. Sub-tasks 3-D1 through 3-D3 each call for data collection from 3-5 living snow fences of various ages and species. Task 3-E and sub-tasks 3-E1 through 3-E3 call for the analysis of this data to identify key factors for the success of living snow fences. This report fulfills the stated deliverables for Tasks 3-D, 3-E, and all associated sub-tasks, and provides data collected from 18 living snow fences across New York State of various species and ages. The key variables of height (H) and optical porosity (P) were measured in the field at each site, and site characteristics and climatic variables were measured remotely, using the protocols developed in Task 3-C and the related sub-tasks of this project. The data collected was analyzed to estimate the snow trapping function of the fences using the models of Tabler (2000, 2003). These models of snow trapping function require metric units of measurement, so all measurements and results were measured and reported in metric units. Tables 2 through 4 are reproduced in Appendix 1 using English units of measurement.

A stratified sample of fences was selected from the statewide list of living snow fence provided by NYSDOT to represent a broad range of fence ages, vegetation types, and locations. Fence age (years since planting) was the predictor variable for the response variables of fence height, optical porosity, and snow storage capacity. Simple linear regressions were performed to test the null hypothesis that the slope of the regressions was equal to zero. The null hypothesis was rejected and regressions were reported as significant when the p value was less than or equal to 0.05 ($p \leq 0.005$). Scatter plots, r^2 values, and fitted equations for the regression models were

produced in the Minitab statistical software program. Regressions for each response variable were performed amongst all fences, and also grouped by vegetation type. It was expected that, amongst all fences, there would be a strong positive relationship between age and height, a strong negative relationship between age and porosity, and a strong positive relationship between age and capacity. In addition to linear regressions, non-linear regressions were performed for the predictor variable of capacity/transport ratio versus the response variables of downwind drift length in drift model 1, and downwind drift length in drift model 2. A list of all regressions performed and the corresponding r^2 values, p values, and S values were included in Table 5.

Fence Location, Species, and Planting Pattern

The 18 living snow fences investigated for this research were located in six NYSDOT regions and 10 counties within in New York State (Figure 1, Table 1). Each fence was assigned an identification tag using the name of the town the fence was located in, followed by the vegetation type, and the age (years since planting) of the fence (i.e. Spencerport-conifer-6). If more than one fence was investigated in the same town, a letter, starting with “A”, was added after the name of the town (i.e. Preble-A-willow-9). The highway number, side of the road the fence was planted on (i.e. south bound), and the approximate NYSDOT highway reference marker at which the fence begins were also included in Table 1. Photos taken at a number of sites are included in Appendix 2.

Seven shrub-willow cultivars, five conifer species, one honeysuckle cultivar, and one corn cultivar were investigated (Table 2). Fence age (years since planting) ranged from 1 - 11 years, constituting an eleven year chronosequence. Fence length ranged from 67 - 482 m and the mean

was 237 m \pm 115 m. Eleven fences consisted of two rows; four fences consisted of a single row; two fences consisted of three rows; and the corn fence consisted of eight rows. Plant spacing and row spacing of shrub-willow fences was 0.61 m and 0.76 m respectively. The one exception was Grand-Gorge-willow-7, which consisted of a single row of shrub-willow at 0.31 m plant spacing. Amongst the six conifer fences, plant spacing ranged from 1.83 – 3.66 m. For conifer fences with multiple rows, three fences had 3.05 m row spacing and one fence had 2.13 m row spacing.

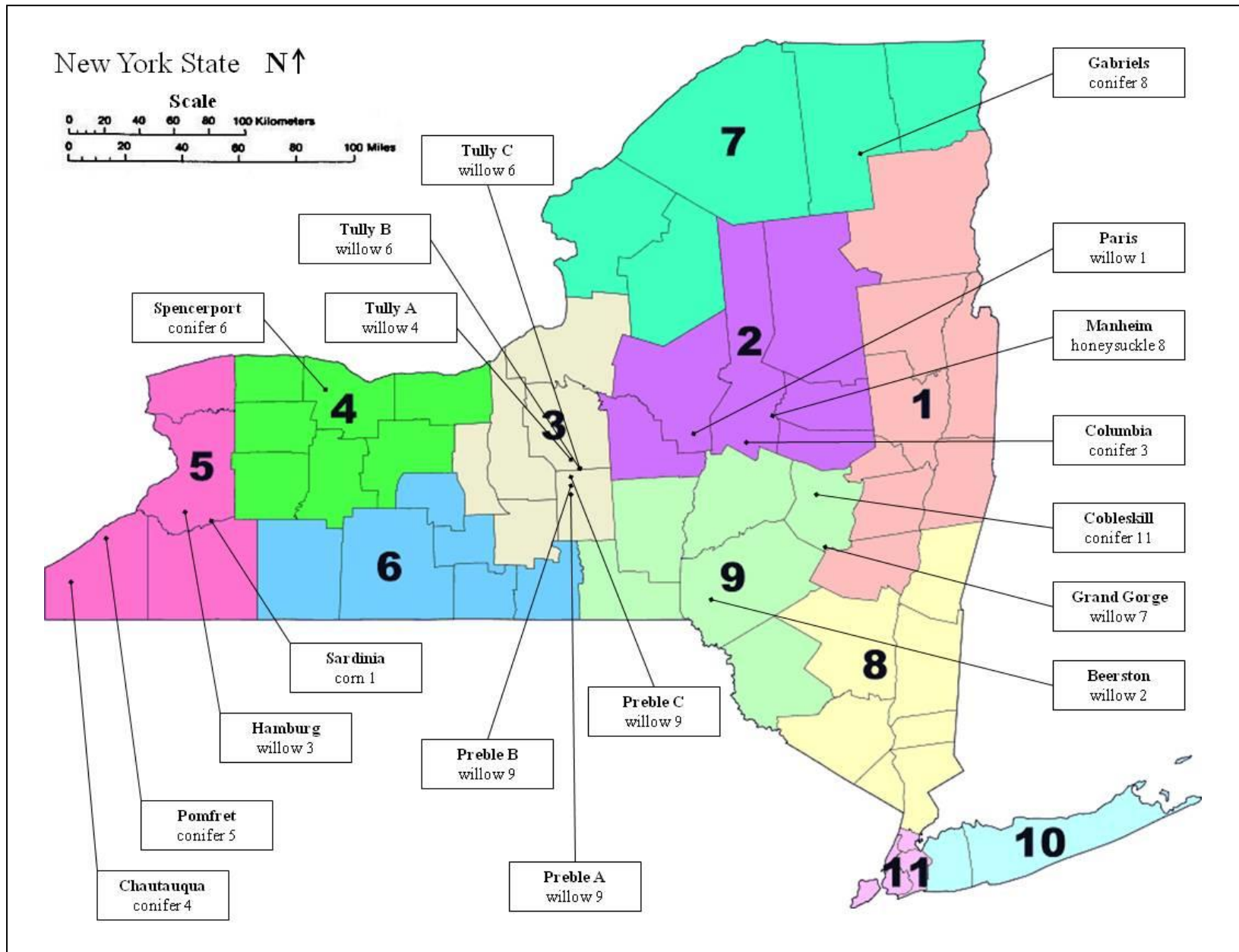


Figure 1: Map of New York State showing NYSDOT regions, approximate locations, and identification tags (town name, vegetation type, age) of the 18 living snow fences investigated for this research

Table 1: Fence identification tags and location data of 18 living snow fences investigated in this research, sorted by NYSDOT region and county

NYSDOT Region	County	Fence Identification Tag (Town - vegetation type - age)	Highway Number	Highway Side	NYSDOT Reference Marker Start
2	Herkimer	Columbia - conifer - 3	28	SB	28 2304 1067
2	Herkimer	Manheim - honeysuckle - 8	167	SB	167 2302 3024
2	Oneida	Paris - willow - 1	12	SB	12 260 41119
3	Cortland	Preble A - willow - 9	I-81	SB	81I 3202 3090
3	Cortland	Preble B - willow - 9	I-81	SB	81I 3202 3086
3	Cortland	Preble C - willow - 9	I-81	SB	81I 3202 3084
3	Onondaga	Tully A - willow - 4	I-81	SB	81I 3303 1020
3	Onondaga	Tully B - willow - 6	281	SB	281 3302 1011
3	Onondaga	Tully C - willow - 6	281	SB	281 3302 1011
4	Monroe	Spencerport - conifer - 6	531	WB	531 430 12017
5	Chautauqua	Chautauqua - conifer - 4	394	EB	17 5201 1055
5	Chautauqua	Pomfret - conifer - 5	60	SB	60 5201 3244
5	Erie	Hamburg - willow - 3	219	SB	219 531 21112
5	Erie	Sardinia - corn - 1	16	SB	16 5302 1009
7	Franklin	Gabriels - conifer - 8	86	SB	86 7201 1047
9	Delaware	Beerston - willow - 2	10	EB	10 930 11218
9	Delaware	Grand Gorge - willow - 7	30	SB	30 9502 1010
9	Schoharie	Cobleskill - conifer - 11	I-88	WB	88I 9507 1081

Table 2: Taxonomy and planting pattern of 18 living snow fences investigated in this study, sorted by vegetation type and age (years since planting)

Fence Identification Tag (Town - vegetation type - age)	Scientific Name	Common Name	Fence Length (m)	Plant Spacing (m)	Number of rows	Row Spacing (m)	Fetch Distance (m)
Sardinia - corn - 1	<i>Zea mays</i>	standing corn rows	350	0.10	8	0.75	340
Manheim - honeysuckle - 8	<i>Lonicera tatarica</i>	Arnold red honeysuckle	181	0.91	1	-	206
Paris - willow - 1	<i>Salix purpurea, Salix miyabeana</i>	var. SX64, Fishcreek	115	0.61	2	0.76	275
Beerston - willow - 2	<i>Salix miyabeana, Salix purpurea</i>	var. SX64, Fishcreek	410	0.61	2	0.76	128
Hamburg - willow - 3	<i>S. sachalinensis, S. dasyclados</i>	var. SX61, 98101-61	264	0.61	2	0.76	780
Tully A - willow - 4	<i>Salix miyabeana, Salix purpurea</i>	var. SX64, Fishcreek	482	0.61	2	0.76	750
Tully B - willow - 6	<i>Salix caprea hybrid</i>	var. S365	235	0.61	2	0.76	185
Tully C - willow - 6	<i>S. sachalinensis x S. miyabeana</i>	var. Sherburne	235	0.61	2	0.76	185
Grand Gorge - willow - 7	<i>Salix purpurea</i>	shrub-willow purpurea	158	0.31	1	-	171
Preble A - willow - 9	<i>S. miyabeana, S. sachalinensis</i>	var. SX64, SX61, 98101-61, 9870-42	192	0.61	2	0.76	480
Preble B - willow - 9	<i>S. miyabeana, S. sachalinensis</i>	var. SX64, SX61, 98101-61, 9870-42	115	0.61	2	0.76	370
Preble C - willow - 9	<i>S. miyabeana, S. sachalinensis</i>	var. SX64, SX61, 98101-61, 9870-42	116	0.61	2	0.76	538
Columbia - conifer - 3	<i>Picea abies</i>	Norway spruce	67	3.05	3	2.13	855
Chautauqua - conifer - 4	<i>Picea pungens</i>	blue spruce	185	3.66	3	3.05	620
Pomfret - conifer - 5	<i>Picea pungens</i>	blue spruce	140	3.66	2	3.05	437
Spencerport - conifer - 6	<i>Pseudotsuga menziesii</i>	Douglas-fir	373	1.83	1	-	157
Gabriels - conifer - 8	<i>Thuja occidentalis</i>	northern white cedar	345	2.13	1	-	470
Cobleskill - conifer - 11	<i>Abies concolour</i>	white fir	302	3.05	2	3.05	318
Mean 5.7	-	-	237	1.3	2	1.3	404
Median 6.0	-	-	235	0.6	2	0.8	370
Standard Deviation 3.0	-	-	117	1.2	1.6	1.0	230

Fence Height and Porosity

There was a significant positive linear relationship ($p < 0.001$) between age and height (**H**) amongst all fences as expected (Figure 2). The height of Sardinia-corn-1 was the lowest of any fence including a shrub-willow fence of the same age (Paris-willow-1) (Table 3). Manheim-honeysuckle-8 fell approximately 2 m below the height trend amongst all fences. Conifer fences were fairly evenly distributed above and below the trend. Shrub-willow fences were concentrated above or slightly below the trend. Preble-C-willow-9 had the largest observed height of any fence. Cobleskill-conifer-11 was slightly shorter than Spencerport-conifer-6, Grand-Gorge-willow-7, Preble-A-willow-9, and Preble-B-willow-9. In general, willow fences had a slightly faster height growth rate ($\text{Height} = 8.644 + 0.5753 \text{ Age}$, $r^2 = 0.852$, $p < 0.001$) than the trend amongst all fences. Height of conifer fences generally increased with age, but there was no significant relationship between age and height amongst conifer fences ($p = 0.149$).

When the observed height of fences (**H**) was compared to predicted values of required fence height [$\mathbf{H}_{\text{req}} = (\mathbf{Q}/8.5)^{0.455}$] at 50% porosity, the observed height was greater than the required height for every fence investigated in this research (Figure 3, Table 3). The mean required height was 1.0 m plus or minus (\pm) 0.3 m, but the observed height was 3.8 m \pm 1.7 m. Paris-willow-1 had 0.5 m of excess height beyond the required amount, and Beerston-willow-2 had 1.3 m of excess height. Columbia-conifer-3 had 1.6 m of excess height. For all fences ages five and older, the observed height was approximately two to six times greater than the required height (Figure 3). Sardinia-corn-1 had 0.4 m of excess height. Manheim-honeysuckle-8 had 1.4 m in excess height despite being well below the trend of height growth amongst all fences.

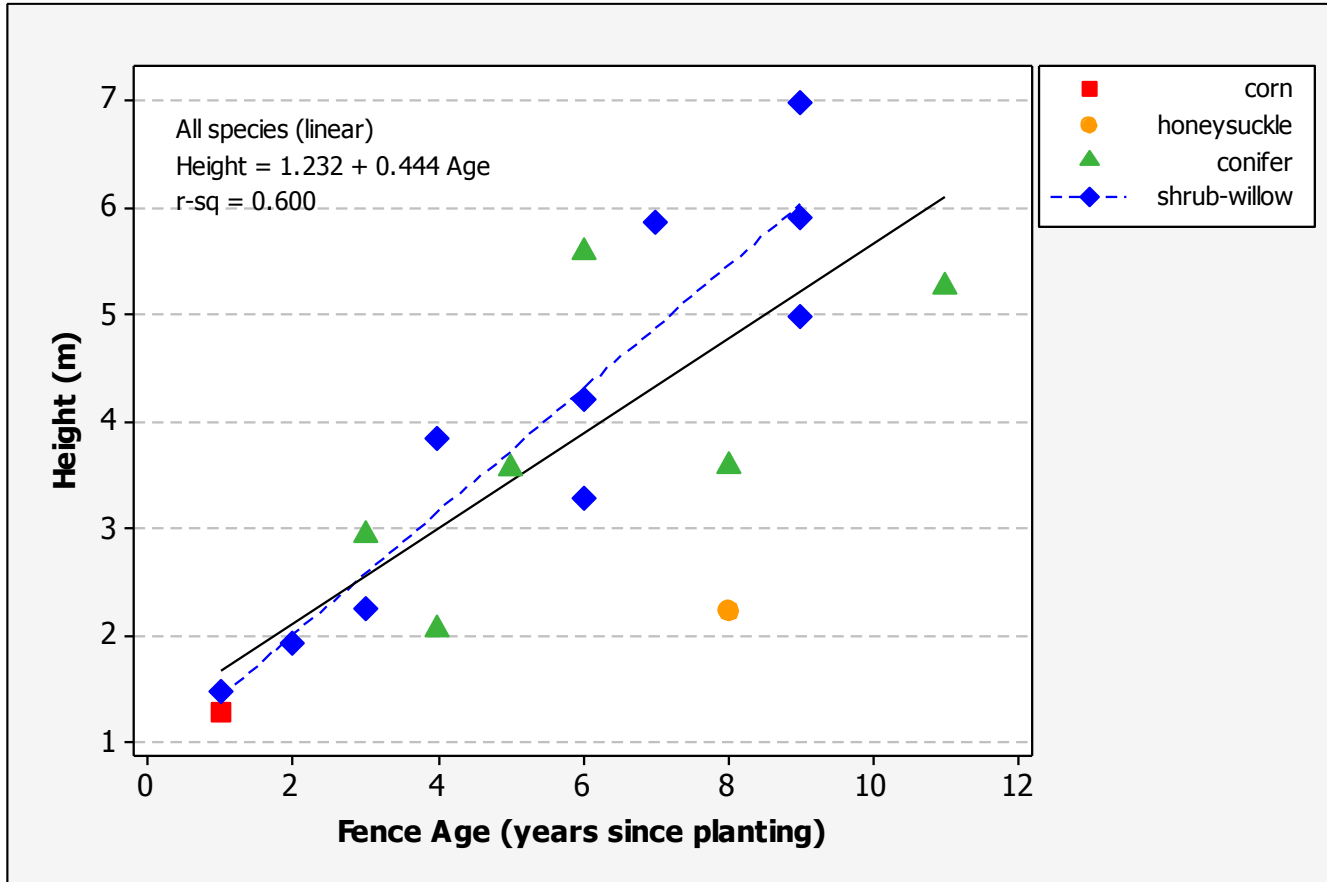


Figure 2: Age (years since planting) versus height (**H**) of 18 living snow fences of various species in New York State, grouped by vegetation type

Table 3: Summary of results for variables related to snow trapping function of 18 living snow fences of various species in New York State, sorted by vegetation type and age (years since planting)

	H_{req}	H	P	Q_c[*]	Q[*]	Q_c/Q[*]
Fence Identification Tag (Town - Vegetation Type - Age)	Required Height (m)	Observed Height (m)	Porosity	Capacity (t/m)	Transport (t/m)	Capacity/Transport Ratio
Sardinia - corn - 1	0.9	1.3	0%	5	7	<1
Manheim - honeysuckle - 8	0.8	2.2	63%	47	5	10
Paris - willow - 1	1.0	1.5	92%	<1	8	<1
Beerston - willow - 2	0.6	1.9	88%	<1	3	<1
Hamburg - willow - 3	1.5	2.3	77%	29	19	1.5
Tully A - willow - 4	1.2	3.9	52%	167	13	13
Tully B - willow - 6	0.7	3.3	61%	113	4	30
Tully C - willow - 6	0.7	4.2	62%	192	4	50
Grand Gorge - willow - 7	0.7	5.9	47%	411	4	110
Preble A - willow - 9	0.9	5.0	33%	239	7	34
Preble B - willow - 9	1.0	5.9	39%	387	9	44
Preble C - willow - 9	1.1	7.0	26%	430	10	43
Columbia - conifer - 3	1.3	2.9	27%	66	15	4
Chautauqua - conifer - 4	1.2	2.1	61%	40	12	3
Pomfret - conifer - 5	0.9	3.6	41%	130	7	19
Spencerport - conifer - 6	0.7	5.6	29%	280	3	82
Gabriels - conifer - 8	1.4	3.6	39%	128	17	8
Cobleskill - conifer - 11	1.0	5.3	38%	297	8	39
Mean	<i>1.0</i>	<i>3.8</i>	<i>50%</i>	<i>185</i>	<i>9</i>	<i>27</i>
Median	<i>1.0</i>	<i>3.6</i>	<i>50%</i>	<i>167</i>	<i>8</i>	<i>16</i>
Standard Deviation	<i>0.3</i>	<i>1.7</i>	<i>20%</i>	<i>141</i>	<i>5</i>	<i>31</i>

Note* - The **Q_c** and **Q** values reported in this table were rounded to the nearest t/m for clarity. The capacity/transport ratios (**Q_c/Q**) reported in this table are the rounded ratio of the *actual* capacity and transport values modeled in this study

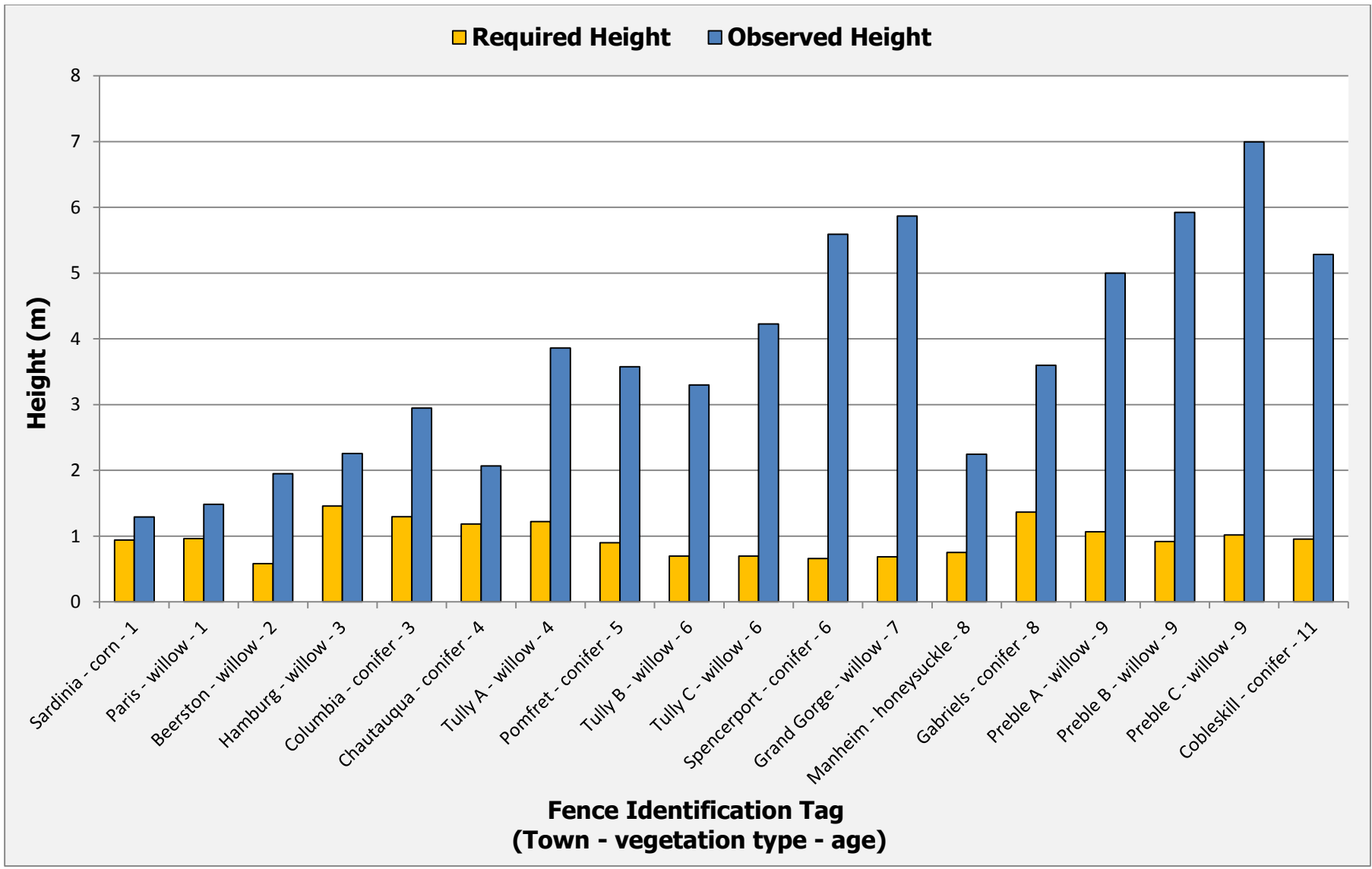


Figure 3: Observed height (H) compared to the predicted required height (H_{req}) of 18 living snow fences of various species and ages (years since planting) in New York State

There was a significant negative relationship ($p = 0.005$) between age and porosity (**P**) across 17 fences in this research (Figure 4). This was the expected result based on the fact that vegetation generally fills in open space (porosity) over time as plants grow. Sardinia-corn-1 was excluded from this regression due to the observed porosity value of 0% (non-porous) at age 1, which made it a distinct outlier from all other porosity values (Figure 4). This low porosity value was due to the small plant spacing, and eight-row planting pattern (five more rows than any other fence) (Table 2). Columbia-conifer-3 was substantially below the porosity trend amongst all fences, due to the small spacing, three-row configuration, and the large size of trees three years after planting. The other conifer fences were near or below the trend line. Shrub-willow fences were near or above the trend up to age 7. Of the three age 9 shrub-willow fences, one was near the trend line and two were below it.

Manheim-honeysuckle-8 fell substantially above the trend amongst all species due to the single-row configuration and 0.91 m plant spacing. By comparison, the three other single-row fences (one shrub-willow and two conifer fences) were similar ages, but had had lower porosities than Manheim-honeysuckle-8 (Table 3). Compared to the trend amongst all fences, porosity of shrub-willow fences declined more rapidly and consistently (Porosity = $0.976 - 0.0712 \text{ Age}$, $r^2 = 0.892$, $p < 0.001$) (Figure 4). There was no significant relationship between age and porosity amongst conifer fences ($p = 0.877$) indicating that porosity for fences of this vegetation type changed very little between ages 3 and 11.

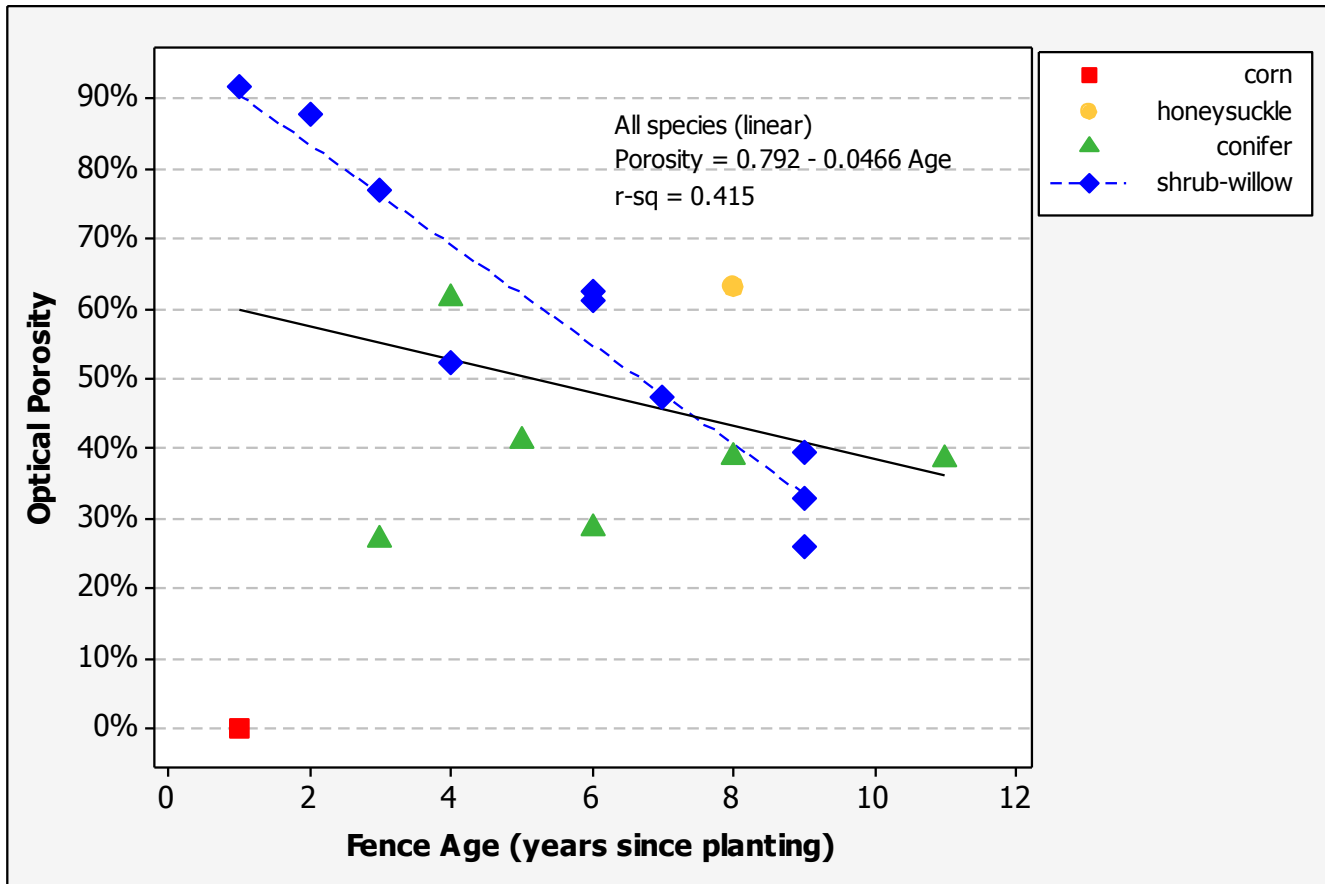


Figure 4: Age (years since planting) versus optical porosity (**P**) of 18 living snow fences of various species in New York State, grouped by vegetation type

Fence Capacity and Snow Transport

There was a strong positive linear relationship ($p < 0.001$) between age and capacity (Q_c) amongst all fences investigated in this research (Figure 5). The trend in capacity was similar to the trend in height as expected, capacity being primarily driven by height and slightly modified by porosity [$Q_c = (3 + 4P + 44P^2 - 60P^3) H^{2.2}$]. Conifer fences were near or below the trend line of all fences, the one exception being Spencerport-conifer-6 which was ~100 t/m above the trend. Shrub-willow fences were near the trend line of all fences, with the exceptions of Grand-Gorge-willow-7, Preble-B-willow-9 and Preble-C-willow-9, all three of which had capacity over 350 t/m and were ~100 t/m above the trend. Manheim-honeysuckle-8 was ~150 t/m below the

capacity trend of all fences, and had a capacity similar to age 3 conifer and shrub-willow fences. Capacity of shrub-willow fences increased over time at a slightly faster rate than the trend amongst all fences ($\text{Capacity} = -77.9 + 49.0 \text{ Age}$, $r^2 = 0.769$, $p = 0.001$). Capacity of conifer fences increased at a slightly slower rate than the trend amongst all fences ($\text{Capacity} = -12.2 + 27.5 \text{ Age}$, $r^2 = 0.554$, $p = 0.090$).

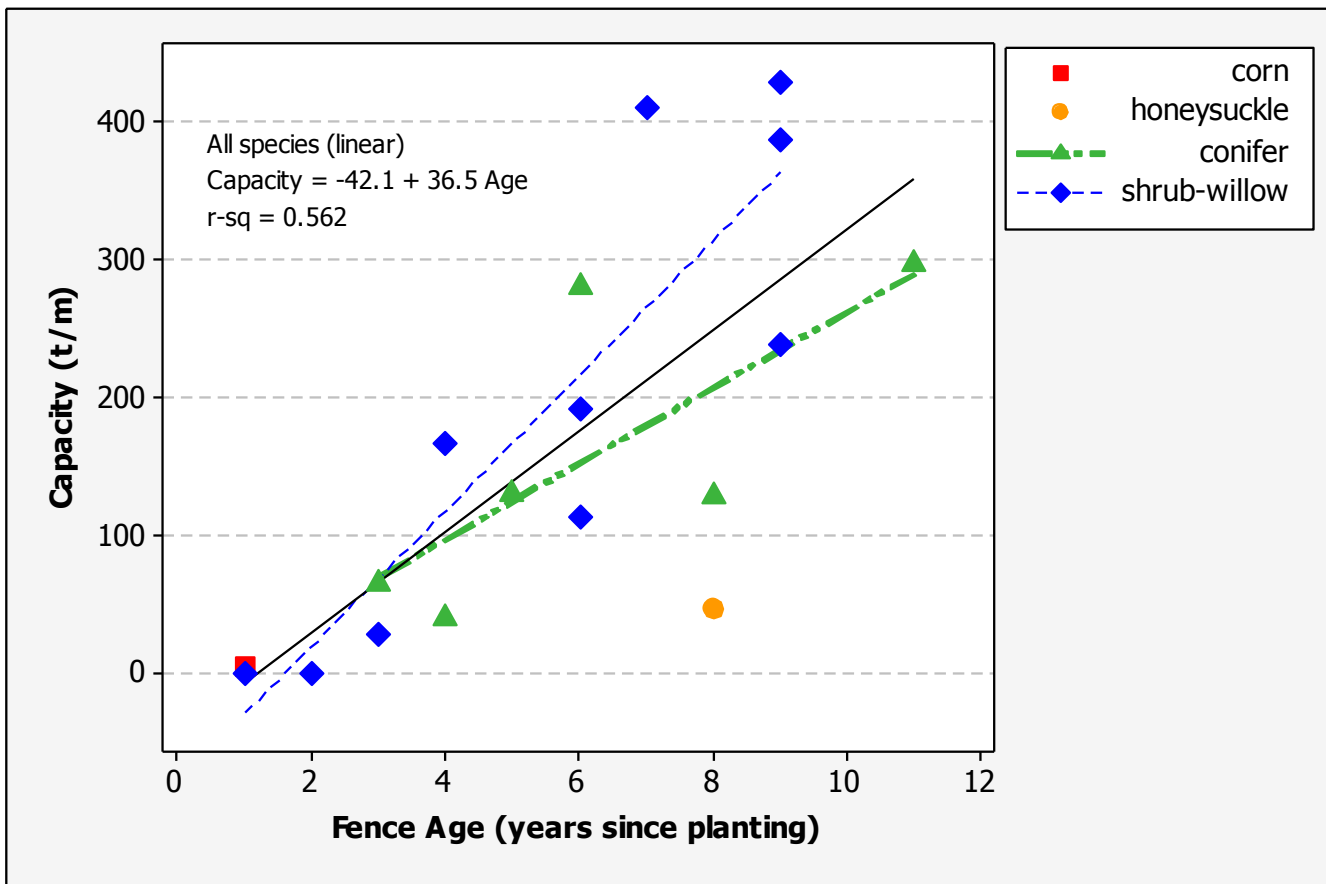


Figure 5: Age (years since planting) versus capacity (Q_c) of 18 living snow fences of various species in New York State, grouped by vegetation type

Snow transport (Q) across all sites ranged from 3 - 19 t/m, and the mean was 9 t/m ± 5 t/m (Table 3, Figure 5) [$Q = 1500(0.17)(S_{we,AS})(1-0.14^{F/3000})$]. This range of seasonal snow transport

values was classified as “very light” (<10 t/m), or “light” (10 - 19 t/m), by Tabler (2003) in terms of the severity of blowing snow problem. Snow transport (Q) of Sardina-corn-1 was 7 t/m, which was greater than the fence capacity of 5 t/m. The height (H) of Sardina-corn-1 exceeded the required fence height (H_{req}), but the *low* porosity value of 0% (non-porous) reduced the storage capacity. The capacities of age 1 and age 2 shrub-willow fences (Paris-willow-1 and Beerston-willow-2) were both below 1 t/m which was less than the snow transport at these sites. The height of these fences again exceeded the required fence height, but *high* porosity values of 92% and 88% negated any substantial storage capacity. All fences in this research age 3 and older had capacity values that exceeded transport (Table 3, Figure 6) indicating that fences were fully functional ($Q_c \geq Q$) at early ages.

The capacity/transport ratio (Q_c/Q) of Hamburg-willow-3 was 1.5:1 (Figure 7), meaning that after three growing seasons, the storage capacity of this fence was 1.5 times the quantity of snow transport occurring at the site in average year. The Q_c/Q ratio of Columbia-conifer-3 was 4:1 after three growing seasons. The Q_c/Q ratio for Tully-A-willow-4 was 13:1, nearly 10 times the Q_c/Q ratio at Hamburg-willow-3, which was the same vegetation type and only one year younger. The second youngest conifer fence Chautauqua-conifer-4 had a Q_c/Q ratio of only 3:1, but the third youngest conifer fence (Pomfret-conifer-5) was 19:1. For all fences age five and older, the Q_c/Q ratio was between 8:1 and 110:1, indicating that fences had large amounts of excess storage capacity at early ages. The largest Q_c/Q ratios were observed at Grand-Gorge-willow-7 (110:1), and Spenerport-conifer-6 (82:1). All capacity/transport ratios were partly a result of the capacity of the fences, but also the transport values which were slightly different at each site. For example, Spenerport-conifer-6 was near the median age, had one of the *highest*

capacity values, but also equaled the *lowest* transport value which combined to give it the second highest Q_s/Q ratio amongst all fences. Overall, the fences investigated in this research had snow storage capacity greater than the site transport after three growing seasons, and continued to add excess storage capacity in a linear trend over the eight subsequent years of the chronosequence, further increasing the Q_s/Q ratio.

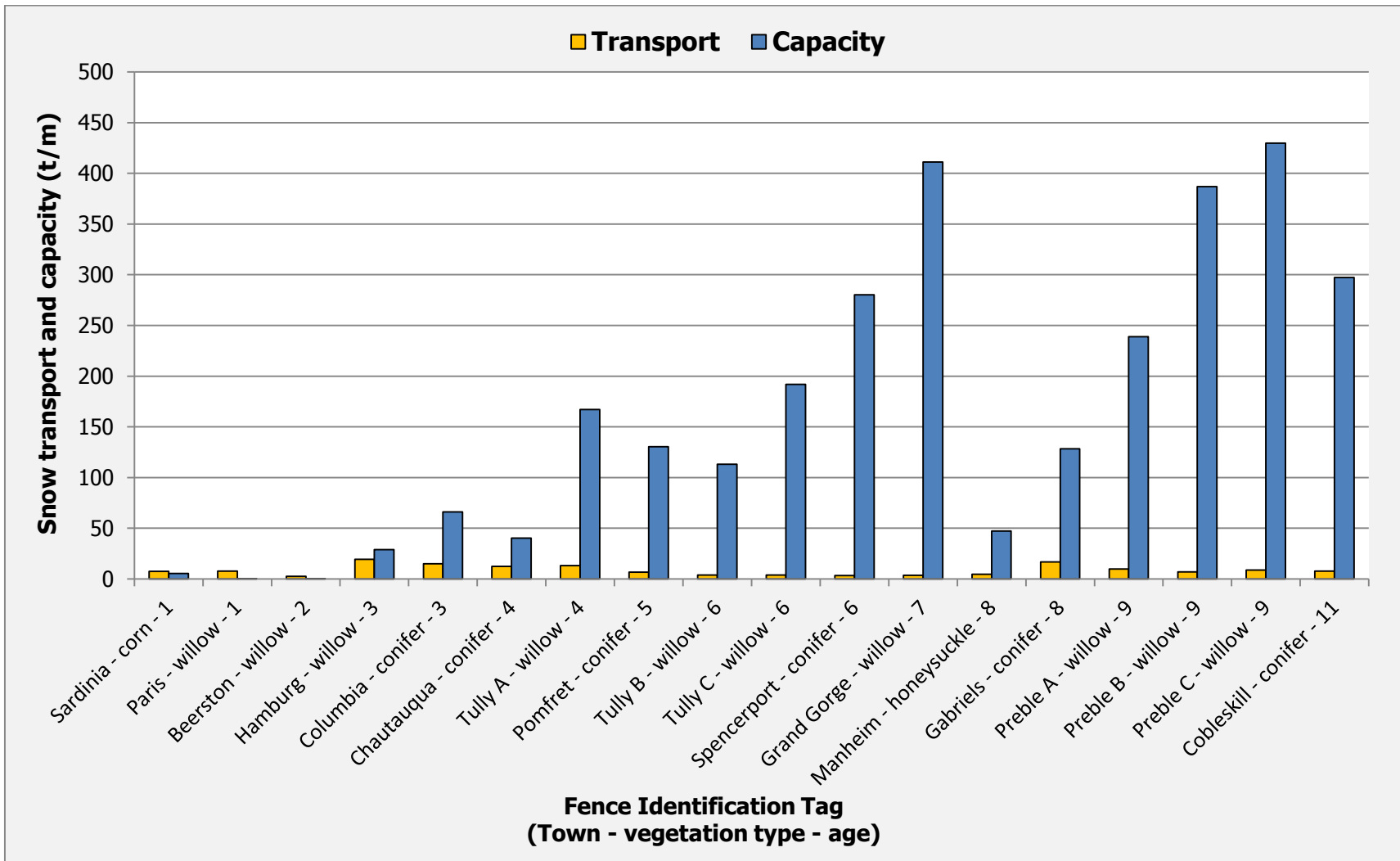


Figure 6: Fence capacity (Q_c) relative to the quantity of snow transport (Q) at each site for 18 living snow fences of various species and ages (years since planting) in New York State

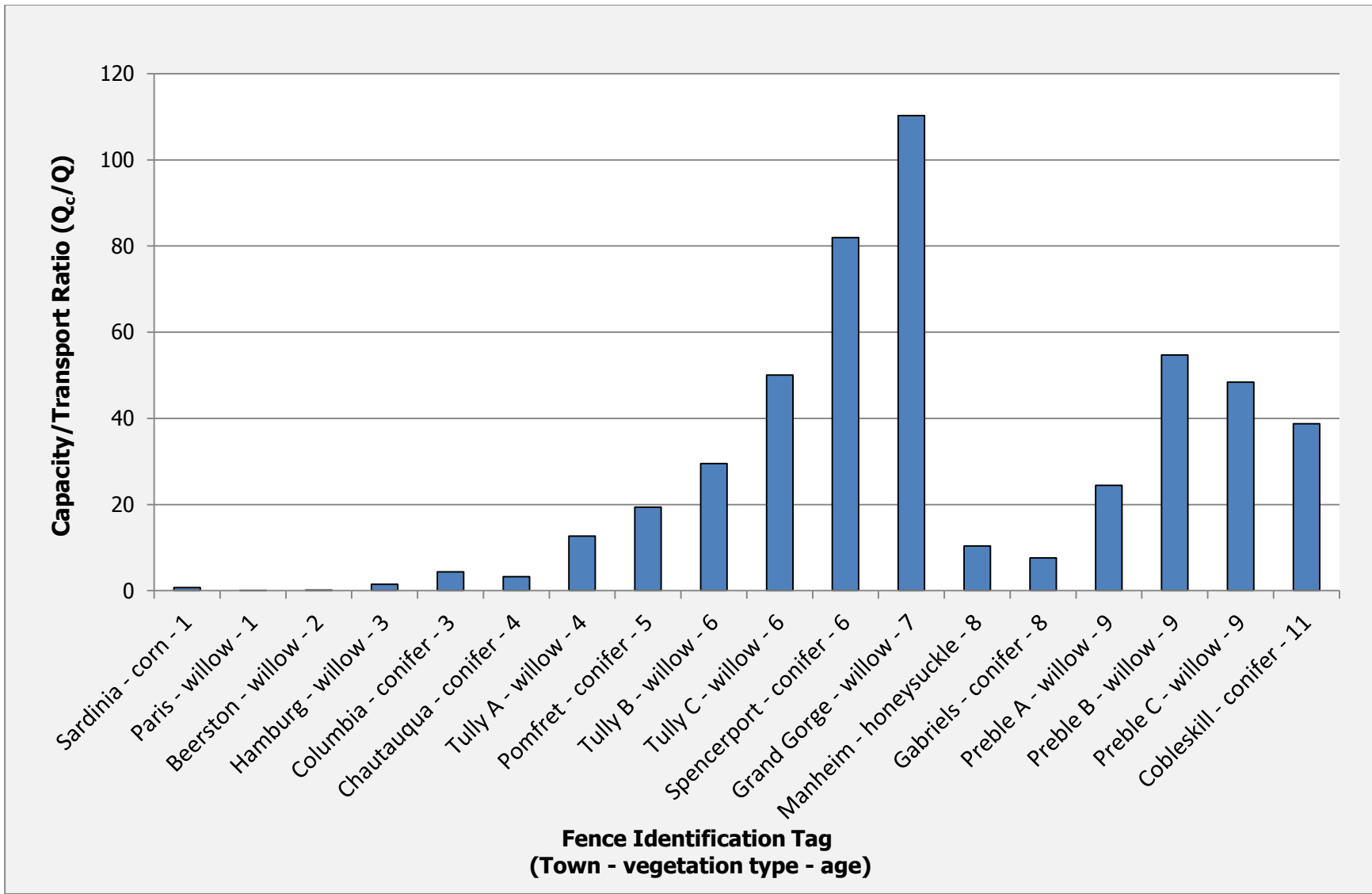


Figure 7: Capacity/Transport ratio (Q_c/Q) of 18 living snow fences of various species and ages (years since planting) in New York State

Setback Distance and Predicted Drift Length

There was no significant relationship between observed setback distance (**D**) and the predictor variables of height (**H**), capacity (**Q_c**), snow transport (**Q**), capacity/transport ratio (**Q_c/Q**), nor predicted setback (**D₃₅**) ($p > 0.417$). This indicates that there is no standard methodology or model being consistently applied in the selection of setback distances for living snow fences in New York State. The choice of setback distances was likely influenced by site conditions and limitations, but likely also reflects the literature on living snow fences which provides no consensus nor precise guidelines on this topic. Observed setback (**D**) ranged from 9 m to 95 m. The range of *predicted* setback values (**D₃₅**) was considerably smaller at 18 m - 46 m. The mean of observed setback distances was 34 m \pm 24 m (Table 4). The mean of *predicted* setbacks was 30 m, which was only 4 m less than the observed mean. However, the standard deviation of predicted values was only \pm 8 t/m, compared to the larger standard deviation of observed values of \pm 24 t/m. Observed setback values thus showed a large maximum value, a large range, and a large standard deviation.

When the length of the downwind drift (**L**) was predicted for all fences using *drift model 1*, the mean drift length was 42 m \pm 12 m (Table 4). The range of predicted drift lengths produced by drift model 1 was 25 m to 68 m. The drift length values produced by drift model 1 were *larger* than the observed setback distance for 12 out of 18 fences in this study, and larger than the predicted setback (**D₃₅**) for 14 of 18 fences.

$$\text{[Drift Model 1: } L = ([10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)(H)\text{]}$$

Table 4: Observed setback, predicted setback, and drift model outputs of 18 living snow fences of various species in New York State, sorted by vegetation type and age (years since planting)

Fence ID Tag (Town - Vegetation Type - Age)	Observed Setback Distance (D) (m)	Predicted Setback Distance (D₃₅) (m)	Predicted Drift Length Model 1 (m)	Predicted Drift Length Model 2 (m)	Capacity/Transport Ratio (Q_c/Q)
Sardinia - corn - 1	71	29	25	18	<1
Manheim - honeysuckle - 8	38	24	25	8	10
Paris - willow - 1	26	30	52	34	<1
Beerston - willow - 2	27	18	68	20	<1
Hamburg - willow - 3	28	46	47	30	1.5
Tully A - willow - 4	42	38	41	13	13
Tully B - willow - 6	10	22	34	7	30
Tully C - willow - 6	10	22	44	7	50
Grand Gorge - willow - 7	95	22	57	7	110
Preble A - willow - 9	13	33	43	9	34
Preble B - willow - 9	10	29	54	8	44
Preble C - willow - 9	9	32	53	8	43
Columbia - conifer - 3	52	41	28	12	4
Chautauqua - conifer - 4	59	37	28	16	3
Pomfret - conifer - 5	31	28	34	9	19
Spencerport - conifer - 6	37	21	44	5	82
Gabriels - conifer - 8	17	43	36	14	8
Cobleskill - conifer - 11	41	30	48	9	39
Mean	<i>34</i>	<i>30</i>	<i>42</i>	<i>13</i>	<i>27</i>
Median	<i>31</i>	<i>30</i>	<i>43</i>	<i>9</i>	<i>16</i>
Standard Deviation	<i>24</i>	<i>8</i>	<i>12</i>	<i>8</i>	<i>31</i>

There was no significant relationship ($p = 0.136$) between capacity/transport ratio and the drift length outputs produced by drift model 1 (Figure 8). When the capacity/transport ratio of fences was between 0 and 15:1 in drift model 1, the drift length output ranged between 25 m and 68 m. When capacity/transport ratio was greater than 15:1 in drift model 1, drift length generally *increased* and ranged between 25 m and 57 m. This general increase in drift length was *not* consistent with the expected trend of decreasing drift length in response to increasing capacity/transport ratio in accordance with the stages of drift formation from Tabler (2003).

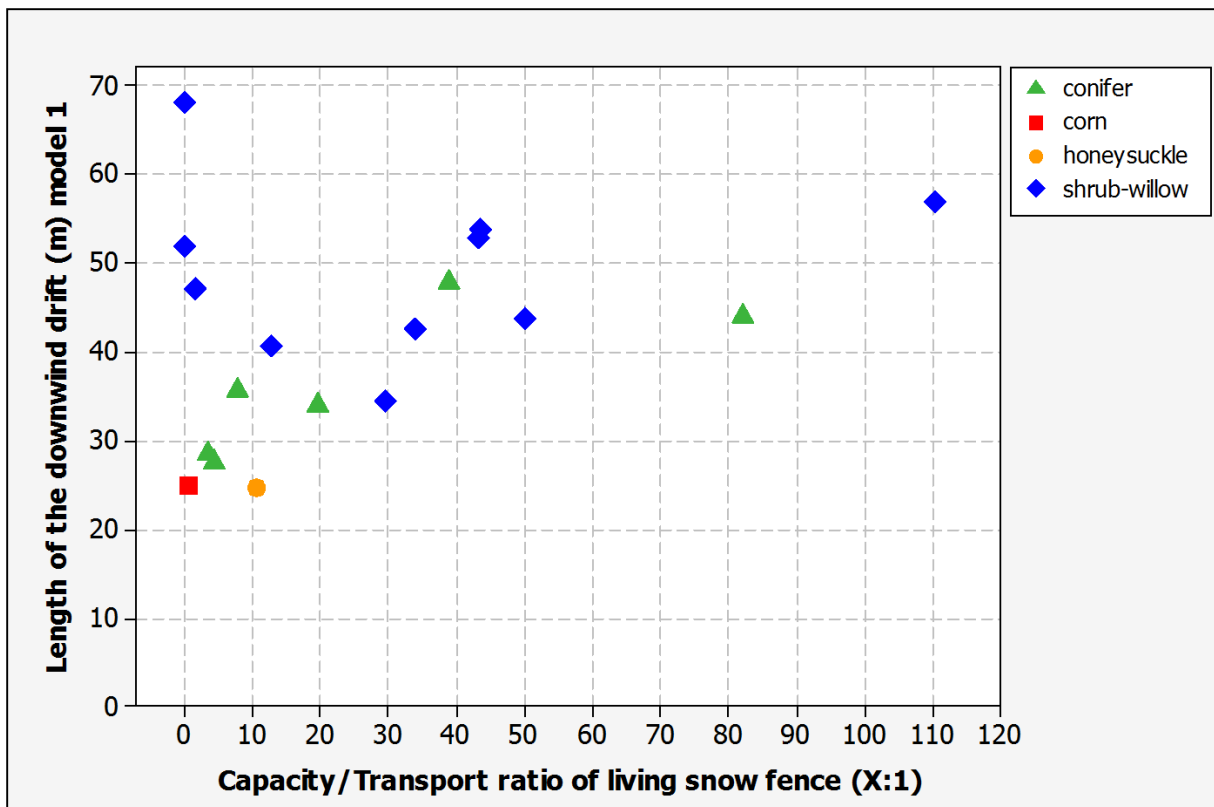


Figure 8: Capacity/Transport ratio versus length of the downwind snow drift as predicted by drift model 1 for 18 living snow fences of various ages (years since planting) and species in New York State

When drift length (**L**) was predicted for all fences using *drift model 2*, the mean drift length was 15 m ±8 m. The range of predicted drift lengths produced by model 2 was 5 m - 34 m. The drift length values produced by drift model 2 were *smaller* than the observed setback distance for 16 out of 18 fences in this study, and smaller than the predicted setback (**D₃₅**) for 16 of 18 fences (Table 4).

$$\text{[Drift Model 2: } L = ([10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)(H_{req})]$$

There *was* significant negative relationship ($p = 0.006$) between capacity/transport ratio and the drift length outputs produced by model 2 (Figure 9). The relationship between capacity/transport ratio and drift length in drift model 2 was best fit to an asymptomatic trend line. The standard error of the non-linear regression was $S = 4.037$, indicating that the predicted drift length values fell a standard distance of approximately ±4 meters from the trend line.

When capacity/transport ratio (Q_c/Q) of fences was between 0 and 15:1 in drift model 2, drift length declined rapidly from 34 m to 8 m. When capacity/transport ratio was greater than 15:1 in drift model 2, drift length was less than 10 m. The overall trend in capacity/transport ratio versus drift length produced by drift model 2 met the expected outcome according to the stages of drift formation in which drift length *decreases* with increasing capacity/transport ratio. The consistency of drift lengths below 10 m in drift model 2 indicates that fences with capacity/transport ratios greater than 15:1 likely do not exceed the first stage of drift formation (Figure 11), and the majority of seasonal snow transport is stored on the upwind side of the fence and in close proximity downwind of the fence. The variable of porosity is included in drift model 2, but porosity did not have a substantial effect on drift lengths, indicating that

capacity/transport ratio was the key variable influencing drift length for the fences and conditions investigated

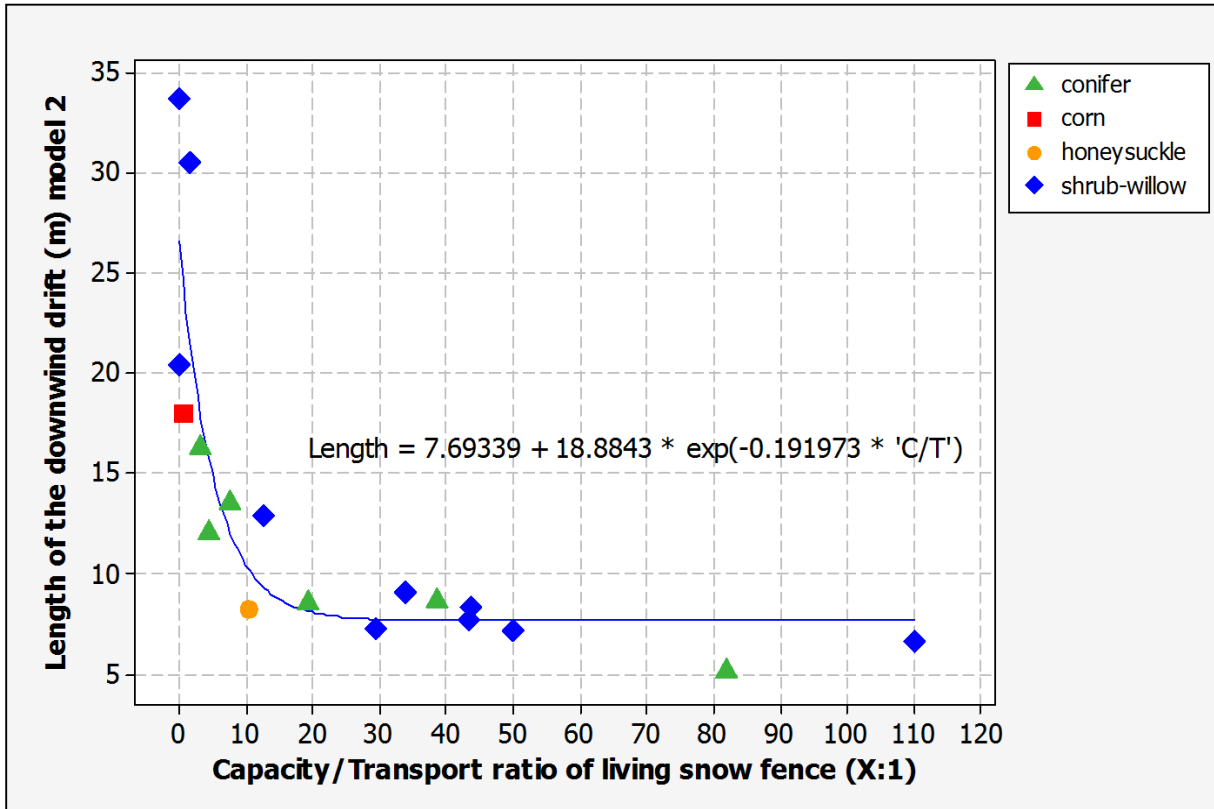


Figure 9: Capacity/Transport ratio (Q_c/Q) versus length of the downwind snow drift as predicted by drift model 2 for 18 living snow fences of various ages (years since planting) and species in New York State

Table 5: Summary of regressions, p values, r² values, and S values for all fences, shrub-willow fences, and conifer fences

	All Fences		Shrub-willow Fences		Conifer Fences	
Simple Linear Regressions (predictor versus response)	p	r ²	p	r ²	p	r ²
Age versus Height	<0.001	0.600	<0.001	0.852	0.149	-
Age versus Porosity	0.005	0.415	<0.001	0.892	0.877	-
Age versus Capacity	<0.001	0.562	0.001	0.769	0.090	0.554
	All Fences					
Non-Linear Regressions (predictor versus response)	p	S				
Capacity/Transport Ratio versus Drift Length (drift model 1)	0.136	-				
Capacity/Transport Ratio versus Drift Length (drift model 2)	0.006	4.037				

Discussion

Functionality and Benefits of Living Snow Fences

Height and porosity are the key structural variables that influence snow trapping, the primary benefit of living snow fences. The time lag until height and porosity values equate to fully functional snow fences, where fence capacity is greater than or equal to average annual snow transport ($Q_c \geq Q$), is an important consideration in the use and design of living snow fences. The results of this research showed that the height and porosity of shrub-willow and conifer living snow fences in New York State was sufficient to create fully functional fences ($Q_c > Q$) three years after planting (Figures 1,2,4,5,6). This result confirms Volk et al. (2006) which states that known shrub-willow growth rates and stem counts will produce functional snow fences 2 - 3 years after planting with proper establishment. By contrast, the majority of literature states that living snow fences take five to seven years or longer to begin functioning (USDA 2012), and even longer to become fully functional ($Q_c \geq Q$). Living snow fences investigated in this research were fully functional at younger ages than what is commonly reported in the literature, due in part to light transport conditions across all 18 research sites. Sites with higher transport conditions may increase the time until fences become fully functional, but fence capacity (Q_c) was over 100 t/m for 11 snow fences investigated, and eight fences had capacity large enough to be fully functional even in “severe” transport conditions of 160 – 320 t/m (Tabler 2003).

Living snow fences therefore have the potential to become fully functional at ages much younger than what is commonly reported in the literature when best management practices are employed. This includes techniques mentioned in previous publications (see Tabler 2003, Gullickson et al. 1999) that are still being actively developed and improved for living snow

fences. Such techniques include: thorough site assessments including soil sampling; selection of species ideal for living snow fences and closely matched to site conditions; thorough site preparation techniques including the suppression of existing vegetation, soil preparations, and soil amendments; proper planting techniques for each vegetation type; prevention of browse by deer and other animals; and proper post-installation monitoring and maintenance for 2-3 years after planting to ensure that fences become established and achieve optimal growth rates (Heavey and Volk 2013).

Thus living snow fences and shrub-willow fences in particular have the potential to produce benefit-cost ratios and net present values that exceed those reported by Daigneault and Betters (2000), and reduce or contain the annual budget for snow and ice control in New State and other states in which is billions spent annually nationwide. Two potential drawbacks of using shrub-willow fences are that they require a relatively high degree of maintenance in the years immediately after planting, and may have shorter life cycles than conifer fences, potentially decreasing their benefit-cost ratios and net present values. The large snow trapping capacity shortly after planting of willow fences is enhanced by proper monitoring and maintenance. Living snow fences planted with conifer *seedlings* may require similarly high levels of post-planting care to reduce weed competition for sunlight and physical resources, but conifer fences planted with larger potted or balled trees may require less post-planting care, potentially offsetting some of the costs associated with purchasing and installing larger trees.

Living snow fences are generally expected to have longer functional life cycles than structural snow fences, an important factor in their economic feasibility (Tabler 2003). Shrub-willows are “pioneer species”, which may limit their functional life cycles as living snow fences

as a natural tradeoff to rapid juvenile growth rates. However, with a potential life cycle of 20 years or longer, and the full functionality and large amounts of excess storage capacity at early ages observed in this research, shrub-willow living snow fences should be able to produce favorable economic returns on investment *when best management practices are employed*. The coppice potential of shrub-willow fences also represents an opportunity for regenerating fences and extending their lifecycles. Conifer living snow fences, in contrast to shrub-willows, are generally more “climax species” that may have much longer functional life cycles as living snow fences, potentially increasing their benefit-cost ratios and net present values. Installing large conifer trees, as opposed to seedlings, will create snow trapping more quickly, but will also increase the cost of purchasing and installing the trees.

The corn and honeysuckle fences in this research were limited to one fence of each vegetation type, but the height growth and capacity of fences in this limited sample was notably less than shrub-willow and conifer fences. Corn fences are ultimately limited to the height and capacity that can be achieved in one growing season. Sardinia-corn-1 also appeared to have been reduced from its full height (and capacity) by early winter 2012/2013 when the fence was investigated, with the tops of the corn broken off or folded over, likely from a combination of weather conditions (rain saturation, snow loads, wind, freeze/thaw cycles, etc) and herbaceous plant characteristics (lack of woody tissue). The outcome of this characteristic of vegetation type was that the fence did not have enough storage capacity to be fully functional when combined with the non-porous 8 row planting configuration. A second strip of corn left standing at a distance of 50 m upwind or downwind of the first strip, as recommended by Tabler

(2003), would have likely increased the storage capacity of this fence to fully functional levels ($Q_c > Q$) despite the reduced height, but would have also increased the (annual) cost of this fence.

The living snow fence Manheim-honeysuckle-8 had sufficient capacity to be fully functional under the estimated site transport, but was well below the trend in height and capacity amongst all fences, and above the trend in porosity. The fence also had a large bottom gap due to the plant morphology, plant spacing, and single-row configuration. The observed bottom gap does not meet the desired morphological characteristic for living snow fences of a ground-level branching pattern, which may negatively impact the snow trapping function of this fence by allowing wind and snow to pass through the bottom gap until it becomes filled in with snow. In general, honeysuckle appears to be a vegetation type that creates living snow fences with functional snow storage capacity in a reasonable time frame for light snow transport conditions, but with the potential for bottom gaps and high porosity if multiple rows are not used, and slower growth rates and lower capacities relative to shrub-willow and conifer fences.

Setback and Drift Length

Despite slight differences in the rate of height growth and porosity exclusion amongst different vegetation types, fences investigated in this research had sufficient capacity to be considered fully functional ($Q_c > Q$) by age 3 (three years after planting), and continued to add excess capacity in a linear trend for the remaining 8 years of the chronosequence. These fences are expected to continue to add more height growth and excess capacity in the future, further increasing the observed capacity/transport ratios which were between 8:1 and 110:1 for fences age 5 and older. These findings have important implications for the design

of living snow fences in regards to drift length and the required setback distance which is driven by the interplay of height, porosity, and capacity/transport ratio (Tabler 2003).

The range of observed setback distances (**D**) in this research was three times the range of *predicted* setback values [$\mathbf{D}_{35} = (\sin\alpha)35\mathbf{H}_{\text{req}}$]. This indicates that there is likely more variation than necessary in the setbacks observed in the field. This variation is likely due in part to site limitations, but also likely reflects the lack of consensus in the literature on how to determine a proper setback for living snow fences. The maximum observed setback distance was *twice* the maximum predicted value (**D**₃₅) (Table 4), indicating that some setback distances are excessively large since predicted setback (**D**₃₅) is a conservatively large estimate of setback that does not account for reduced drift lengths created by large capacity/transport ratios. There was no significant relationship between observed and predicted setback; nor between observed setback and height, capacity, or capacity/transport ratio; indicating that setback of living snow fences in New York State is not being consistently selected based on the model of predicted setback (**D**₃₅), nor any other structural variable that would influence the length of the downwind drift. This again reflects the literature outside of Tabler (2003) which rarely provides the model of predicted setback, or any other method for determining an appropriate setback distance for living snow fences. In some cases, the setback of living snow fences in New York State is dictated by the available right of way space, the ability (or inability) to work with land owners to acquire additional planting space, and the presence of utilities or other landscape features than can limit planting space, further complicating the choice of setback and the interpretation of this data.

In many locations however, existing right of way space, which is often 10 m or more, may be sufficient to accommodate the entire length of the downwind drift on living snow fences based on the results of this research. Results showed that the capacity/transport ratios of living snow fences in New York State were between 8:1 and 110:1 for fences age five and older, indicating large amounts of excess storage capacity ($Q_c \gg Q$) at early ages. Large amounts of excess storage capacity is associated with drifts that terminate in the early stages of drift formation, and resulting drift lengths that are a fraction of equilibrium drift length ($35H$) (Figures 10, 11).

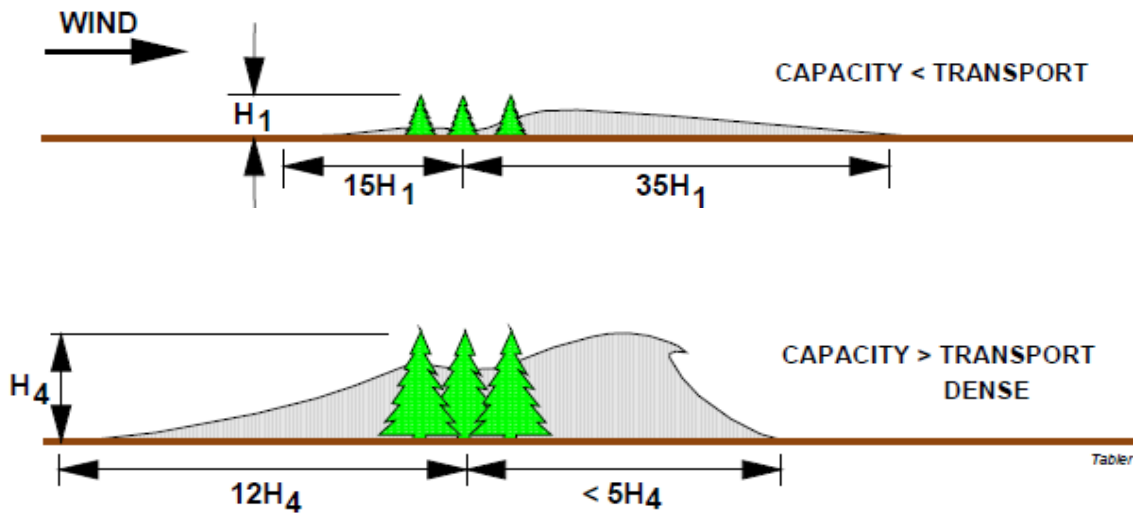


Figure 10: Changes in snowdrift shape and length as a result of changes in fence height, optical porosity, and capacity (Q_c) relative to snow transport (Q) of living snow fences (Diagram from Tabler, 2003)

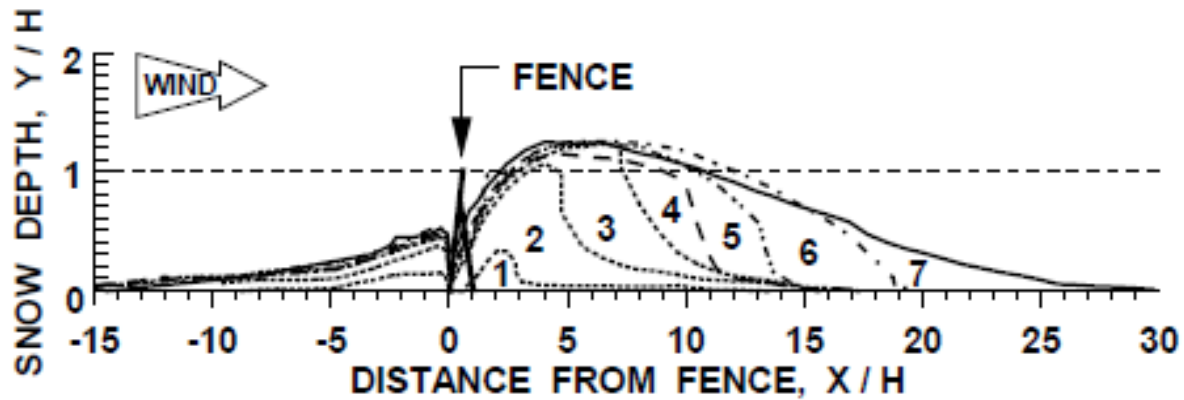


Figure 11: Progressive stages of snow drift formation around a 50% porous barrier
(Diagram from Tabler, 2003)

Tabler (2003) is not explicitly clear as to whether drift model 1 [$L = ([10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)(H)$], or drift model 2 [$L = ([10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)(H_{req})$], is the correct methodology for expressing predicted drift lengths in units of meters, so both possibilities were investigated as part of this research. Drift model 1 produced a series of predicted drift length values that was not significantly correlated with capacity/transport ratio, and did not produce the expected response of a negative relationship between the two variables. The drift lengths produced by model 1 were *larger* than the predicted setback (D_{35}) 78% of the time. This is the opposite of the expected result which should show a *reduced* drift length compared to the conservatively large predicted setback value (D_{35}) which does not account for the influence of capacity/transport ratio.

The drift length values produced by model 1 are not logical when considered in context of the stages of drift formation relative to capacity/transport as ratio discussed in Tabler (2003). When capacity/transport ratio was greater than 15:1 in drift model 1, drift length generally

increased (Figure 8), producing illogical drift length outputs such as drifts 44 m in length when capacity/transport ratio was 50:1; and drifts 57 m in length when capacity/transport ratio was 110:1 (Table 4) under light snow transport conditions. Drift model 1 therefore *cannot* be considered a valid model of predicting drift length in units of meters, and should not be used to predict drift lengths for living snow fences.

In contrast to drift model 1, *drift model 2* produced a logical series of predicted drift length outputs for the fences and conditions investigated in this research. In drift model 2, there *was* a significant negative relationship between capacity/transport ratio and drift length (Figure 9), as expected based on the work of Tabler (2003) (Figure 10, Figure 11). The drift lengths produced by model 2 were *smaller* than the predicted setback 89% of the time, indicating the expected response to capacity/transport ratio in accordance with the stages of drift formation, in which drift length *decreases* in response to increasing capacity/transport ratio. Drift model 2 is therefore the correct interpretation of Tabler (2003) based on the results of this research, and a valid model for estimating the drift length in meters and appropriate setback distance of living snow fences of different heights, porosities, and capacity/transport ratios. The drift length values produced by model 2 are logical and consistent with the stages of drift formation described by Tabler (2003), in that very large capacity/transport ratios produce drift lengths that are substantially *smaller* than predicted setback values (**D35**), indicating that excess capacity of the fence is correctly reducing the predicted length of the downwind drift, which is synonymous with termination of seasonal drift growth in the early stages of drift formation as a result of excess storage capacity (Figure 10, Figure 11).

Drift model 2 showed that when capacity/transport ratio exceeds 15:1, drift length is always less than 10 m. If validated in future research, this is an important result for the design of living snow fences in New York State and beyond. When capacity/transport ratio exceeds 15:1 and drift length does not exceed 10 m. This is likely synonymous with the *first* stage of drift formation illustrated in Figure 11, where approximately 10% or less of the potential fence capacity (Q_c) is occupied by the seasonal snow transport (Q) at the site, and the length of the downwind drift is reduced to a fraction of the maximum 35H setback that is commonly prescribed in the literature. The final piece of this of this research to validate the predicted drift lengths of drift model 2 would be to monitor drift formation around living snow fences of known heights and porosities and compare predicted drift lengths from model 2 to *observed* drift lengths measured in the field. This task was originally included in the objectives of this research, but was not able to be accomplished due to frequent warming and rain events during the winters of 2011/2012 and 2012/2013 which negated any sustained drift growth over the course of the snow season.

If validated with observed values, the data and calculations of this research, the observed capacity/transport ratios, and the predicted influence on drift length from drift model 2 can be easily incorporated into the analysis and design of living snow fences. This offers the potential of a much needed methodology for more precise selection of setback distances to replace the vague and inaccurate generalizations offered in the current literature, and the limited usefulness of the predicted setback model (D_{35}). The trend of fence capacity observed in this research was shown to exceed snow transport after just three growing seasons, and increase capacity/transport ratios to levels of 100:1 or greater over the next eight years. For living snow fence design, drift

model 2 can be used to estimate drift length and required setback distance for any fence of a known or estimated capacity/transport ratio. Likewise, the capacity/transport ratio and other variables of living snow fences of various vegetation types and ages can be estimated using the time series graphs and regression equations from this study, then applied to drift model 2 for design purposes. This would allow snow fence design teams to model the length of the downwind drift over time at different capacity/transport ratios, and select a setback distance that is most appropriate for the site conditions including available planting space and the long term snow and ice control goals of the site.

Using an even more simplified design approach based on the results of this research, if the chosen species and planting pattern of a planned living snow fence is expected to produce a capacity/transport ratio greater than 15:1 in a reasonable time frame, any setback distance 10 m or greater could be assumed adequate to store the estimated snow transport (Figure 9). This may allow the installation of living snow fences in areas where substantial blowing snow problems exist, but available planting space is limited. Calculations of exceedance probabilities could also be easily incorporated into this methodology by simply using a design transport that is some multiple of the estimated site transport when determining the capacity/transport ratio. However, the large capacity/transport ratios observed in this research demonstrate that exceedance probabilities for living snow fences in New York State of common vegetation types such as shrub-willow and conifer fences may be somewhat of an unnecessary calculation, considering that a capacity/transport ratio of 2:1 is equivalent to a less than 0.1% exceedance probability (Tabler 2003), and this capacity/transport ratio is likely to occur very early in the fences life cycle under light transport conditions. Reduced setback distances may limit storage capacity and

increase the exceedance probability during the early years of a living snow fence's life, but capacity would still be greater than zero even with a reduced setback, providing some level of passive snow control before the fence produces large capacity/transport ratios that compensate for the reduced setback distance. However, reduced setback distances could cause drifts around the fence to form on the roadway before the fence grows to the point where large ratios are achieved representing a potential hazard to drivers and a serious safety consideration. The influence of capacity/transport ratios on exceedance probabilities should therefore be considered another important area of future research for living snow fences. The influence of site topography is an important consideration in the design of living snow fences which can limit or increase the snow storage capacity of the fence and influence the choice of setback distance.

Limitations of this Research

The estimates of snow transport in this research were modeled using the key assumptions of the relocation coefficient (C_r) at all sites being equal to the statewide average of 0.17 provided by Tabler (2000); fetch area at all sites being measured at a perpendicular angle to the fence; Tabler's (2000) model of snowfall over the drift accumulation season [$S_{we,AS} = (-695.4 + 0.076 * \mathbf{Elev} + 17.108 * \mathbf{Lat})(0.10)(0.0254)$]; and assumptions of what does and does not constitute wind obstructions that would cause snow deposition and limit the size of the fetch. Another notable limitation of this research is that only fences that could be identified through a combination of remote sensing and field investigations were measured and reported on. This represents a bias for sites that likely had superior plant selection, site quality, planting techniques, and post-planting care. However, the observations of this study, and perhaps even more ideal outcomes for living snow fences, *should* be obtainable for most new living snow

fence installations when proper site analysis, design, plant selection, planting patterns, installation and management practices are employed (see Heavey and Volk 2013).

Finally, the winters of 2011/12 and 2012/2013 produced frequent temperature spikes well above 0° C across New York State, as well as sporadic rain events. These conditions essentially eliminated the possibility of collecting useful data on snow quantities and downwind drift lengths around the living snow fences investigated in this study in those years, but some limited data was collected. Small snow drifts were measured around living snow fences Tully-willow-4, Preble-willow-9, Columbia-conifer-3, and Manhiem-honeysuckle-8 in late February 2013, but snow deposition around the fences was negligible, estimated at substantially less than 1 t/m in all cases. The maximum height of drifts around these fences was approximately 0.3 m and the maximum length of discernible downwind drifts was approximately 2 m.

CONCLUSION

Living snow fences can reduce or contain snow control costs and improve highway safety by disrupting wind patterns and causing controlled deposition of blowing snow in drifts before it reaches the roadway. The key structural variables influencing the snow trapping function of living snow fences are height and optical porosity. This research measured height and porosity on a stratified sample of 18 living snow fences of various ages (years since planting) and vegetation types in New York State. This data was analyzed using the models of Tabler (2000 and 2003) to estimate and interpret the snow trapping function of the fences. Height and

capacity of fences increased linearly with increasing age as expected. Shrub-willow fences increased in height and capacity at a slightly faster rate than the trend amongst all fences. Porosity of fences decreased linearly with age as expected, with shrub-willow fences decreasing at a slightly slower rate than the trend amongst all fences. The estimated snow transport quantities at all sites was classified as very light to light (<20 t/m). Three years after planting, fence capacity was greater than the observed transport at each respective site, indicating that fences were fully functional at ages much earlier than what is commonly reported in the literature. For all fences age five and older, capacity/transport ratios were between 8:1 and 110:1. This substantial amount of excess storage capacity was expected to reduce the length of the downwind drift based on the stages of drift formation described by Tabler (2003). The survival and time until living snow fences become fully functional is highly dependent on proper plant selection and best management practices, which can heavily influence the economic performance and feasibility of living snow fences.

Two models of drift length were investigated, and drift model 2 was found to be a valid model for predicting the influence of capacity/transport ratio on drift length in accordance with the stages of drift formation. This model, which used the *required* fence height (H_{req}) as a coefficient for expressing drift length in units of meters, consistently predicted drift lengths less than 10 m when capacity/transport ratios exceeded 15:1. These drift lengths are much smaller than the setback distances commonly recommended in the literature, and setback distances observed in the field in this research. If this result can be validated in future studies of observed snow deposition and drift length, it can be easily incorporated into the design of living snow fences to more accurately select appropriate setback distances based on predicted drift lengths as

influenced by capacity/transport ratios. This would be a significant contribution to literature, which currently provides no consensus or precise methodology for modeling and selecting appropriate setback distances for living snow fences. This result may also allow more living snow fences to be installed in areas where there are substantial blowing snow problems, but limited right of way space for planting. The time-series graphs and regression equations produced in this research also have the potential to be useful design tools for modeling living snow fence structure and function at various ages.

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Appendix 1 – English Unit Tables

Table 6: English Units - Taxonomy and planting pattern of 18 living snow fences sampled in this study, sorted by vegetation type and age

Fence ID Tag (Town - vegetation type - age)	Scientific Name	Common Name	Fence Length (ft)	Plant Spacing (ft)	Number of rows	Row Spacing (ft)	Fetch Distance (ft)
Sardinia - corn - 1	<i>Zea mays</i>	standing corn rows	1148	4"	8	2' 6"	1115
Manheim - honeysuckle - 8	<i>Lonicera tatarica</i>	Arnold red honeysuckle	594	3'	1	-	676
Paris - willow - 1	<i>Salix purpurea, Salix miyabeana</i>	var. SX64, Fishcreek	377	2'	2	2' 6"	902
Beerston - willow - 2	<i>Salix miyabeana, Salix purpurea</i>	var. SX64, Fishcreek	1345	2'	2	2' 6"	420
Hamburg - willow - 3	<i>S. sachalinensis, S. dasyclados</i>	var. SX61, 98101-61	866	2'	2	2' 6"	2559
Tully A - willow - 4	<i>Salix miyabeana, Salix purpurea</i>	var. SX64, Fishcreek	1581	2'	2	2' 6"	2461
Tully B - willow - 6	<i>Salix caprea hybrid</i>	var. S365	771	2'	2	2' 6"	607
Tully C - willow - 6	<i>S. sachalinensis x S. miyabeana</i>	var. Sherburne	771	2'	2	2' 6"	607
Grand Gorge - willow - 7	<i>Salix purpurea</i>	shrub-willow purpurea	518	1'	1	-	561
Preble A - willow - 9	<i>S. miyabeana, S. sachalinensis</i>	var. SX64, SX61, 98101-61, 9870-42	630	2'	2	2' 6"	1575
Preble B - willow - 9	<i>S. miyabeana, S. sachalinensis</i>	var. SX64, SX61, 98101-61, 9870-42	377	2'	2	2' 6"	1214
Preble C - willow - 9	<i>S. miyabeana, S. sachalinensis</i>	var. SX64, SX61, 98101-61, 9870-42	381	2'	2	2' 6"	1765
Columbia - conifer - 3	<i>Picea abies</i>	Norway spruce	220	10'	3	7'	2805
Chautauqua - conifer - 4	<i>Picea pungens</i>	blue spruce	607	12'	3	10'	2034
Pomfret - conifer - 5	<i>Picea pungens</i>	blue spruce	459	12'	2	10'	1434
Spencerport - conifer - 6	<i>Pseudotsuga menziesii</i>	Douglas-fir	1224	6'	1	-	515
Gabriels - conifer - 8	<i>Thuja occidentalis</i>	northern white cedar	1132	7'	1	-	1542
Cobleskill - conifer - 11	<i>Abies concolour</i>	white fir	991	10'	2	10'	1043
Mean 5.7	-	-	778	4' 3"	2	4' 4"	1325
Median 6.0	-	-	771	2'	2	2' 7"	1214
Standard Deviation 3.0	-	-	384	4'	1.6	3' 3"	755

Table 7: English Units - Summary of results for variables related to snow trapping function of 18 living snow fences of various species in New York State, sorted by vegetation type and age

	H_{req}	H	P	Q_c*	Q*	Q_c/Q*
Fence ID Tag (Town - Vegetation Type - Age)	Required Height (ft)	Observed Height (ft)	Porosity	Capacity (tons/ft)	Transport (tons/ft)	Capacity/Transport Ratio
Sardinia - corn - 1	3'	4' 3"	0%	1	2	<1
Manheim - honeysuckle - 8	2' 7"	7' 3"	63%	16	2	10
Paris - willow - 1	3' 3"	4' 11"	92%	<1	3	<1
Beerston - willow - 2	2'	6' 3"	88%	<1	1	<1
Hamburg - willow - 3	5'	7' 6"	77%	10	6	1.5
Tully A - willow - 4	4'	12' 10"	52%	56	4	13
Tully B - willow - 6	2' 3"	10' 10"	61%	38	1	30
Tully C - willow - 6	2' 3"	13' 10"	62%	65	1	50
Grand Gorge - willow - 7	2' 3"	19' 4"	47%	138	1	110
Preble A - willow - 9	3'	16' 5"	33%	80	2	34
Preble B - willow - 9	3' 3"	19' 4"	39%	130	3	44
Preble C - willow - 9	3' 7"	23'	26%	144	3	43
Columbia - conifer - 3	4' 3"	9' 6"	27%	22	5	4
Chautauqua - conifer - 4	4"	6' 11"	61%	13	4	3
Pomfret - conifer - 5	3"	11' 10"	41%	44	2	19
Spencerport - conifer - 6	2' 3"	18' 4"	29%	94	1	82
Gabriels - conifer - 8	4' 7"	11' 10"	39%	43	6	8
Cobleskill - conifer - 11	3' 3"	17' 5"	38%	100	3	39
Mean	3' 3"	12' 6"	50%	62	3	27
Median	3' 3"	11' 10"	50%	56	3	16
Standard Deviation	1'	5' 7"	20%	47	2	31

Note* - The **Q_c** and **Q** values reported in this table were rounded to the nearest ton/ft (short ton per linear foot) for clarity. The capacity/transport ratios (**Q_c/Q**) reported in this table are the rounded ratios of the *actual* capacity and transport values, the same as reported in Table 3

Table 8: English Units - Observed setback, predicted setback, and models of drift length of 18 living snow fences of various species in New York State, sorted by vegetation type and age

Fence ID Tag (Town - Vegetation Type - Age)	Observed Setback Distance (D) (ft)	Predicted Setback Distance (D₃₅) (ft)	Predicted Drift Length Model 1 (ft)	Predicted Drift Length Model 2 (ft)	Capacity/Transport Ratio (Q_c/Q)
Sardinia - corn - 1	233	95	82	59	<1
Manheim - honeysuckle - 8	125	79	82	26	10
Paris - willow - 1	85	98	171	112	<1
Beerston - willow - 2	89	59	223	66	<1
Hamburg - willow - 3	92	151	154	98	1.5
Tully A - willow - 4	138	125	135	43	13
Tully B - willow - 6	33	72	112	23	30
Tully C - willow - 6	33	72	144	23	50
Grand Gorge - willow - 7	312	72	187	23	110
Preble A - willow - 9	43	108	141	30	34
Preble B - willow - 9	33	95	177	26	44
Preble C - willow - 9	30	105	174	26	43
Columbia - conifer - 3	171	135	92	39	4
Chautauqua - conifer - 4	194	121	92	52	3
Pomfret - conifer - 5	102	92	112	30	19
Spencerport - conifer - 6	121	69	144	16	82
Gabriels - conifer - 8	56	141	118	46	8
Cobleskill - conifer - 11	135	98	157	30	39
Mean	<i>112</i>	<i>98</i>	<i>138</i>	<i>43</i>	<i>27</i>
Median	<i>102</i>	<i>98</i>	<i>141</i>	<i>30</i>	<i>16</i>
Standard Deviation	<i>79</i>	<i>26</i>	<i>39</i>	<i>26</i>	<i>31</i>

Appendix 2 – Photos of Living Snow Fences



Figure 12: Living snow fence Sardinia-corn-1 from the leeward side of the fence in winter 2012/2013



Figure 13: Living snow fence Columbia-conifer-3 in winter 2012/2013



Figure 14: View leeward side of living snow fence Tully-A-willow-4 in winter 2012/2013



Figure 15: Small snow drifts formed around living snow fence Manheim-honeysuckle-8 in winter 2012/2013



Figure 16: Living snow fence Gabriels-conifer-8 (northern white cedar) in late fall 2012



Figure 17: Wide angle view of living snow fence Cobleskill-conifer-11 in fall 2011

All Photos by Justin P. Heavey

Task 3-F: Benefit-Cost Model

A benefit-cost model for LSF was also created as Task 3-F of this project. The model was tested and revised and example scenarios run using the model have shown that willow LSF and LSF of other vegetation types can have positive net present values and benefit-cost ratios through cost savings of reduced snow and ice control measures. LSF can also produce other public benefits such as reduced accidents rates, avoidance of reduced travel speeds, and the provision of environmental benefits that can increase the sustainability of transportation projects. The benefit-cost model was created by itemizing the costs associated with the best practice protocols for LSF installation and maintenance established in this study, and the machinery/logistics of snow and ice control by NYSDOT. Other variables were included in the model based on transportation standards to quantify benefits from LSF related to value travel time savings (VTTS) and accident reduction factor (ARF). The model was presented to NYSDOT staff via a webinar and improvements were made to the model based on comments and discussions from the project's technical working group. The model is available for download on the project website at (www.esf.edu/willow/lsf). Screen shots of the model are provided below.

LSF Cost-Benefit Model 2014 - Excel

Living Snow Fence Project Inputs

Model Parameters (required)

Length of highway segment	1.00	miles
Length of snow fence	5280	feet
Project discount rate	5.00%	

Living Snow Fence Costs

Installation Costs by Task

	Equipment Rate (\$/hr)	Labor Rate (\$/hr)	Year 0		sub-totals
			Hours	Materials (\$/ft)	
Site analysis and design	\$0	\$20	40	\$0.00	\$800
Clear existing vegetation	\$50	\$20	4	\$0.00	\$280
Herbicide	\$50	\$20	4	\$0.25	\$1,600
Subsoil	\$50	\$20	4	\$0.00	\$280
Soil amendments/fertilizer	\$50	\$20	16	\$0.75	\$5,080
Rototill	\$50	\$20	4	\$0.00	\$280
Weed control fabric	\$50	\$20	8	\$0.25	\$1,880
Planting	\$50	\$20	16	\$0.50	\$3,760
Wood mulch/chips	\$50	\$20	16	\$0.75	\$5,080
Other/flat rate	\$0	\$0	0	\$0.00	\$0
Installation Total:					\$19,040

Maintenance Costs by Task

	Equipment Rate (\$/hr)	Labor Rate (\$/hr)	Year 0			Year 1			Year 2				
			Hours	Materials (\$/ft)	subtotal Year 0	Hours	Materials (\$/ft)	subtotal Year 1	Hours	Materials (\$/ft)	subtotal Year 2		
Mow	\$50	\$20	16	\$0.00	\$1,120	16	\$0.00	\$1,120	16	\$0.00	\$1,120		
Coppice	\$50	\$20	0	\$0.00	\$0	16	\$0.00	\$1,120	0	\$0.00	\$0		
Replant	\$50	\$20	4	\$0.50	\$2,920	0	\$0.00	\$0	0	\$0.00	\$0		
Deer and browse repellent	\$50	\$20	16	\$0.25	\$2,440	16	\$0.25	\$2,440	0	\$0.00	\$0		
Herbicide/pesticide	\$50	\$20	0	\$0.00	\$0	0	\$0.00	\$0	0	\$0.00	\$0		
Fertilize	\$50	\$20	0	\$0.00	\$0	0	\$0.00	\$0	0	\$0.00	\$0		
Irrigation	\$50	\$20	0	\$0.00	\$0	0	\$0.00	\$0	0	\$0.00	\$0		
Monitoring	\$0	\$20	16	\$0.00	\$320	16	\$0.00	\$320	8	\$0.00	\$160		
Other/flat rate	\$0	\$0	0	\$0.00	\$0	0	\$0.00	\$0	0	\$0.00	\$0		
Total Year 0:					\$6,800	Total Year 1:			\$5,000	Total Year 2:			\$1,280

Introduction | **Input** | Output | GreenLITES | Cashflow | Sources

LSF Cost-Benefit Model 2014 - Excel

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General

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Snow and Ice Benefits

Snow and Ice Cost Savings from Living Snow Fence

Average Annual Spot Treatment Cycles for Blowing Snow

Spot treatments per year	25
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Regular Time Labor Cost Per Treatment Cycle

Regular HMW2 labor plus fringe rate	\$20	(\$/hr)
Labor hours expended per cycle	4	(assume heavy dump equipment hours plus 2 hrs. for pre-op/load/unload)
Annual Regular time labor subtotal:	\$1,000	

Over-time Labor Cost Per Treatment Cycle

Labor hours expended per cycle	4	(assume heavy dump equipment hours plus 2 hrs. for pre-op/load/unload)(min. overtime callout of 4 hours)
Annual over-time labor subtotal:	\$1,500	

Equipment Cost Per Treatment Cycle

Hourly rate for single axle heavy dump	\$20	(\$/hr)
Distance from responding facility	20	(miles over the road to beginning of blowing & drifting treatment segment)
Number of lanes in segment treated	2	
Annual Equipment Cost subtotal:	\$840	

Materials Cost Per Treatment Cycle

Snow and Ice materials spread rate:	1	(tons or gallons/lane mile)
Price of Materials:	\$1	(\$/ton or gallon)
Annual Materials Cost:	\$50	

Total Annual Snow and Ice Costs: **\$3,390**

Incremental Snow and Ice Benefits

Reduction in snow & ice costs Year 0	0%
Reduction in snow & ice costs Year 1	0%
Reduction in snow & ice costs Year 2	90%
Reduction in snow & ice costs Year 3	90%
Reduction in snow & ice costs Year 4	90%
Reduction in snow & ice costs Year 5	90%
Reduction in snow & ice costs Year 6	90%
Reduction in snow & ice costs Year 7	90%
Reduction in snow & ice costs Year 8	90%

For years 0-19, enter the expected reduction in snow and ice costs resulting from the living snow fence. Year zero is the first snow season after installation.

Default values are based on figure 4.12 below from Tabler (2003), and observed Qc/Qc values by Heavly (2013). All Qc/Qc values observed on living snow fences across the state were greater than 1.5 after the third growing season (year 2). Qc/Qc ratio is equivalent to a Design Modulus where the exceedance probability K= 1.5, as show in the graph below. K equal to 1.5 indicates fence capacity (Qc) is 1.5 times average annual snow transport (Qt,ave), resulting in a 30% reduction in snow and ice costs, and five percent exceedance capacity of the snow fence filling to capacity.

The design team of the living snow fence project in question can change these values as appropriate.

PROBABILITY OF EXCEEDING STORAGE CAPACITY, Qc (%)

Introduction Input Output GreenLITES Cashflow Sources

READY 70%

LSF Cost-Benefit Model 2014 - Excel

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E59 : 20

Public Benefits (optional)

Safety Benefits

Rates of Accident caused by Blowing and Drifting Snow

Number Annual accidents	1
Accident Reduction Factor of fence	75% (%)

Source: Tabler (2006)... "75% reduction in crash rates in areas protected by snow fences... attributable to the elimination of snowdrifts, improved visibility in blowing snow, and reduced road ice."

Severity Distribution of accidents caused by blowing/driftng snow

Fatal	1.0% (%)
Injury	19.7% (%)
Property Damage Only (PDO)	79.3% (%)

Default values for Accident Severity Distribution and Average Accident Cost are taken from NYSDOT (2010a) for full access, rural, undivided, 2 lane highway. Values for other road types are available at: www.dot.ny.gov/divisions/operating/losses/highway/accident-costs

Average Accident Cost

Fatal	#####
Injury	\$93,500
Property Damage Only (PDO)	\$5,200

Annual Accident Reduction Value: \$42,998

Travel Time Benefits

Traffic Rate

Annual Average Daily Traffic (AADT)	1,000
AADT annual growth rate	5.0% (%)

\$14.93 is the USDOT (2003) value for local auto travel time in 2013 dollars, and @4.17 for truck travel time.

Value Travel Time Savings (VTTs)

Car time value (\$/hr)	\$15.15
Truck time value (\$/hr)	\$24.47
Percent truck travel	0% (%)

Road Closures due to blowing/driftng snow

Annual road closure events	1
Hours of road closure per event	4
Annual value of avoided road closure:	\$2,525

Introduction **Input** Output GreenLITES Cashflow Sources

READY 70%

LSF Cost-Benefit Model 2014 - Excel

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H5 : X ✓ fx Snow & Ice cost savings (avg annual)

Project Output	
Snow & Ice Benefits Only	
Net Present Value	\$2,204
Benefit/Cost Ratio	1
Internal Rate of Return	1%
Payback period (years)	17
Public Benefits Only	
Net Present Value	\$707,369
Benefit/Cost Ratio	23
Internal Rate of Return	79%
Payback period (years)	2
All Benefits (Snow & Ice and Public Benefits)	
Net Present Value	\$741,335
Benefit/Cost Ratio	24
Internal Rate of Return	83%
Payback period (years)	2

Discounted Cost Summaries	
Installation & Maintenance Costs	
Installation (total)	\$19,040
Installation (per mile)	\$19,040
Maintenance (total)	\$12,723
Maintenance (per mile)	\$12,723
Installation + Maintenance (total)	\$31,763
Installation + Maintenance (per mile)	\$31,763

Discounted Benefit Summaries	
Snow & Ice Benefits	
Snow & Ice cost savings (total)	\$33,967
Snow & Ice cost savings (avg annual)	\$1,698
Public Benefits	
Public benefits (total)	\$739,132
Public benefits (avg annual)	\$36,957
All Benefits (Snow & Ice and Public Benefits)	
Total benefits (total)	\$773,098
Total benefits (avg annual)	\$38,655

Introduction Input **Output** GreenLITES Cashflow Sources

READY AVERAGE: 122809.7151 COUNT: 58 SUM: 2947433.163 110%

Appendix A – LSF Show Potential for Large Storage Capacity and Reduced Drift Length Shortly After Planting

Justin P. Heavey
Dr. Timothy A. Volk

Living snow fences show potential for large storage capacity and reduced drift length shortly after planting

Justin P. Heavey
Senior Research Support Specialist
State University of New York - College of Environmental Science and Forestry
Department of Forest and Natural Resource Management
246 Illick Hall
1 Forestry Drive
Syracuse, NY 13210
(315) 399-8879
justinheavey@gmail.com

Timothy A. Volk
Senior Research Associate
State University of New York - College of Environmental Science and Forestry
Department of Forest and Natural Resource Management
246 Illick Hall
1 Forestry Drive
Syracuse, NY 13210

Abstract

Living snow fences are windbreaks designed to mitigate blowing snow problems by trapping snow in drifts before it reaches a road. Research studies on living snow fences are limited and extension publications consequently lack precise design protocols. This study investigated 18 sites in New York State planted with living snow fences of various vegetation types and ages ranging from one to eleven years after planting. Key plant growth variables of fence height and optical porosity were measured along with distance upwind and downwind. This data was combined with site specific snowfall estimates and established equations to calculate the snow storage capacity of each fence, average annual snow transport (blowing snow) at each site, and length of the downwind drift. Capacity/transport ratio of each fence/site was identified as a key variable. Height increased linearly over time and porosity decreased. Three years after planting, height and porosity was sufficient so that capacity/transport ratios were greater than 1:1, indicating substantial snow trapping potential much sooner than commonly reported. Four to eleven years after planting, capacity/transport ratios were between 3:1 and 110:1. Capacity/transport ratios of 15:1 or greater occurred as early as five years after planting and were correlated with estimated drift lengths less than 10 m. The influence of capacity/transport ratio on drift length is not accounted for in current publications and setback recommendations range from 30 - 180 m. The results of this study can improve the understanding, design and function of living snow fences.

Key Words: windbreaks, shelterbelts, trees, shrub willow, *Salix*, transportation

1. Introduction

Living snow fences (LSF) are an agroforestry practice similar to windbreaks (USDA 2011) that uses rows of trees or shrubs to trap blowing snow in drifts before it reaches a road. Blowing snow problems occur around agricultural fields or other large open areas when fallen snow is lifted off the ground and transported by the wind toward a road, a common problem in cold weather regions around the world. This can lead to snow and ice accumulations on the road, reduced visibility, travel delays, automobile accidents and increased road maintenance costs. LSF disrupt wind patterns causing controlled snow deposition in designated areas. Like other agroforestry systems, LSF combine trees and shrubs with agricultural systems, creating numerous economic, social and environmental benefits.

LSF are considered a best practice by transportation agencies (Goodwin 2003; Lashmet 2013) that can reduce or contain the cost of mechanical and chemical snow controls such as plowing and salting (Tabler 2003). Local and state agencies in the United States alone spend over \$2.3 billion annually (2013 US\$) on snow control and nearly \$6 billion annually to repair transportation infrastructure damaged by snow/ice and associated control practices (NCHRP 2005). LSF perform the same snow trapping function as structural (wooden or plastic) snow fences and can have better cost benefit ratios and positive net present values (Daigneault and Betters 2000). LSF can have useful life cycles that exceed structural snow fences by four to seven times (USDA 2011), or 25 years or more (Powell et al. 1992). Many benefits of LSF have both economic and social impacts. In addition to invaluable human life and wellbeing, the average financial cost (2013 US\$) associated with one fatal car accident in New York State is approximately \$3.5 million, and \$93,000 for injury inducing accidents (NYSDOT 2010). Tabler and Meena (2006) reported a 75% reduction in accident rates in areas protected by snow fences. By improving driving conditions and reducing delays and road closures, LSF provide additional benefits in the value of travel time savings (VTTS), a critical factor in the valuation of transportation projects (USDOT 2003). LSF can also provide a variety of environmental and aesthetic benefits (NRCS 2012; Wyatt 2013) as well as value-added agroforestry crops (Streed and Walton 2001).

Despite the potential for multiple benefits, LSF are biological systems that change over time and have not been extensively researched. Suitable site conditions and best practices are required for optimal growth and snow trapping (Gullickson et al. 1999; Tabler 2003; Heavey and Volk 2013). Utilities, land ownership patterns and other landscape elements can limit the feasibility of LSF on many sites. A number of years (growing seasons) after planting are required before snow trapping begins and this can be delayed several years or indefinitely if best practices are not employed. Once established, LSF are susceptible to environmental stressors and disturbances such as pests and drought. Changing plant characteristics and corresponding snow trapping function complicate design decisions, and there is some uncertainty and hesitation around the use of LSF by transportation officials and resource managers. Extension publications lack quantitative protocols and consensus on important design issues such as setback, or the chosen distance between the fence and the roadway.

The objective of this study was to measure key plant growth and site variables for LSF of various vegetation types and years after planting. This data was combined with models developed by Tabler (2000; 2003) to estimate the snow trapping potential of LSF over time including the of number years between planting and snow trapping, snow storage capacity, downwind drift length and required setback distance. Data results and model estimates are discussed in the context of current publications.

2. Materials and Methods

A stratified sample of LSF was selected based on the ability to identify and access sites in the field, and to represent a range of vegetation types and years after planting (**YAP**). Sites were identified using a list of statewide LSF plantings (NYSDOT 2011), geographic information systems (GIS) and site visits. Sites with distinctly low survival rates or stunted growth were excluded in order to evaluate LSF that best represent the dynamics of plant growth and snow trapping potential over time. Once identified, fences

were categorized into four general vegetation types and assigned an identification (ID) tag using the name of the town the fence was located in, a letter for towns with more than one fence/site, the vegetation type, and **YAP** (i.e. Preble-A-willow-9).

The snow trapping variables and terminology used in this study are based on Tabler (2000; 2003) as follows. Height (**H**) is the vertical distance from the ground to the top of the fence vegetation. Optical porosity (**P**) is the percentage of open space when a fence is viewed at a perpendicular angle in winter. Snow storage capacity (**Q_c**) is the estimated quantity of blowing snow that a fence can store per linear meter in units of metric tons of water equivalent per meter (t/m). **Q_c** is primarily a function of **H** and **P** but can be modified by topography and other factors (Tabler 2003). Snow transport (**Q**) is the estimated average annual quantity of blowing snow transported by the wind towards the road in units of t/m. **Q** is a function of fetch distance (**F**), relocation coefficient (**C_r**), and snowfall water equivalent over the drift accumulation season (**S_{we,AS}**). **F** is the distance in meters from the fence to the first obstruction upwind (such as a building or forest) assumed to disrupt wind patterns and cause snow deposition. **C_r** is the estimated fraction of snowfall lifted off the ground and relocated by the wind. **S_{we,AS}** is the estimated snowfall over the period of sustained annual drift growth, delimited by snow that falls before sustained growth or after permanent melt.

Capacity/transport ratio (**Q_c/Q**) influences the length of the downwind snow drift that extends from the fence toward the road (Tabler 2003; Heavey 2013). If **Q_c/Q** is less than or equal to 1:1, maximum downwind drift length is 35H, or 35 times the height of the fence (Tabler 2003), referred to as the equilibrium drift. If **Q_c/Q** is *greater* 1:1, drift length is reduced to some fraction of 35H, making **Q_c/Q** an important variable in the analysis and design of LSF. Setback (**D**) is the distance between the fence and the road selected during the design phase. The estimated length of the downwind drift (**L**) is a function of **H**, **P**, and **Q_c/Q**.

To measure fence and site characteristics, a 100 m sampling plot was established around the linear center point of each fence and a series of eight **H** and **P** measurements, and four **D** and **F** measurements were taken within the plot at equidistant spacing. **D** and **F** were measured remotely using GIS. **D** was measured at a perpendicular angle from the fence to the roadway. **F** was measured at a perpendicular angle from the fence to the first obstacle upwind. **H** was measured using a telescoping measuring pole. Two techniques of measuring **P** were used; a chroma-key technique for corn, honeysuckle and shrub willow LSF; and a high contrast photography technique for conifer LSF. The chroma-key technique consisted of a 1 m wide by 3 m tall backdrop of red synthetic fabric held directly behind the fence to accentuate **P** and maximize the accuracy of photographic samples. Eight photographs were taken within the sampling plot of each fence at approximately the same points where height measurements were taken. The chroma-key technique was not viable for conifer LSF due to differences in morphology of this vegetation type (larger and denser trees). The high-contrast photography methods of Loeffler et al. (1992) were therefore adapted for conifer LSF to produce equivalent photographic samples in which a strong contrast between open (porous) space and vegetation was created (Fig. 1) allowing the percent **P** to be accurately calculated using standard photo editing software. The series of measurements for each variable was averaged for the reported **H**, **P**, **D**, and **F**, representing the mean values for each unique snow fence/site.

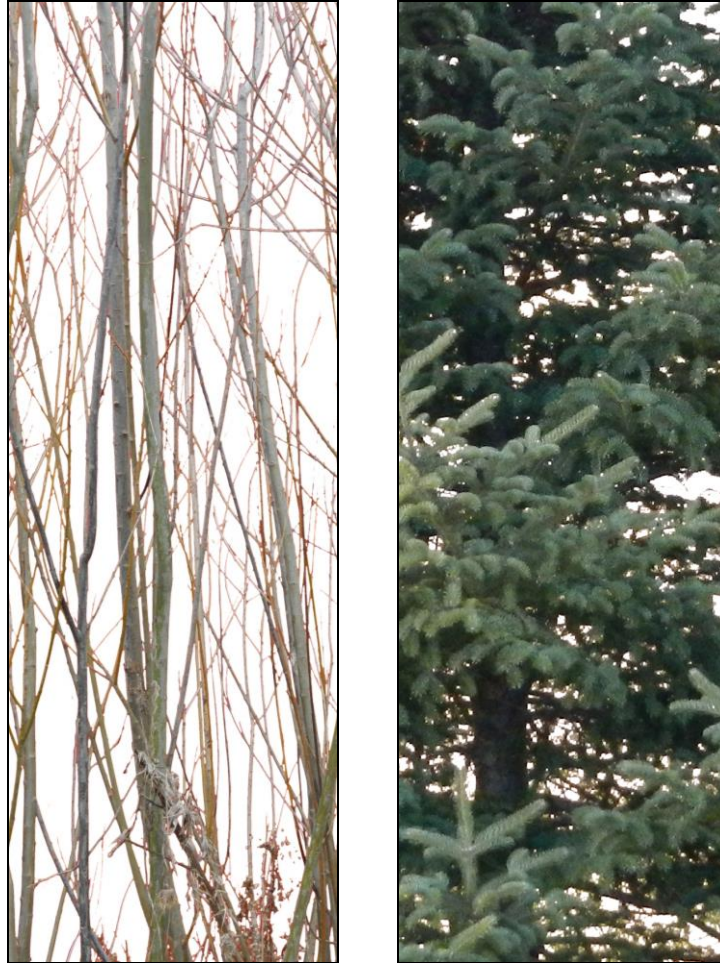


Fig. 1 Examples of processed photos used to measure optical porosity (**P**) from the chroma-key technique (left, Tully-B-willow-6) and high contrast technique (right, Cobleskill-conifer-11)

Mean **H**, **P** and **F** values from each fence/site were modeled using the equations of Tabler (2000; 2003) to estimate **Q_c**, **Q**, and **L**. **Q_c** was estimated using the model from Tabler (2003): $Q_c = (3 + 4P + 44P^2 - 60P^3) H^{2.2}$. Slope was negligible at most sites and no modifications for topography were made to **Q_c**. **Q** was estimated using the model from Tabler (2000): $Q = 1500(C_r)(S_{we,AS})(1-0.14^{F/3000})$. **C_r** of 0.17 was assumed for all sites, representing the statewide average recommended for New York (Tabler 2000). **S_{we,AS}** in the **Q** model was estimated from Tabler (2000): $S_{we,AS} = (-695.4 + 0.076 * \text{Elevation} + 17.108 * \text{Latitude})(0.10)$ and the output of this model was converted from inches to meters.

L was estimated using the model adapted from Tabler (2003): $L = ([10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)(H_{req})$. Required fence height (H_{req}) in the **L** model was estimated from Tabler (2003): $H_{req} = (Q/8.5)^{0.455}$. The **L** model in the current study was modified from the original notation in two ways. Output values in Tabler (2003) are in abstract terms of **L/H**, or drift length relative to fence height. Units of meters are more meaningful when evaluating snow trapping function and required setback distances, so **L/H** values were multiplied by H_{req} to convert the model output into meters. Using H_{req} as a conversion coefficient (as opposed to observed **H**) is considered the correct method based on Heavey's (2013) review of Tabler (2003). Secondly, Q/Q_c is used in the current study in place of A/A_e , which Tabler (2003) describes as equivalent and substitutable ratios (Heavey 2013). Standard setback (**D35**) was estimated from Tabler (2003): $D35 = 35H_{req}$.

Plant growth variables of **H** and **P** were compared to the predictor variable **YAP** using simple linear regression for all fences and by vegetation type for shrub willows and conifers. A positive linear relationship between **YAP** and **H**, and a negative linear relationship between **YAP** and **P** was expected. Non-linear regression was performed for Q_c/Q versus **L** to evaluate the relationship between capacity/transport ratio and drift length. A quadratic regression was performed for **YAP** versus **L** to estimate drift length in various years after planting, which was then compared to **D** and **D35** for each fence/site. All statistical analysis and figures were produced using Minitab 16.2.

3. Results

LSF were measured at 18 sites across New York State (Table 1) including ten shrub willow, six conifers, one corn, and one honeysuckle. The number of years after planting (**YAP**) ranged from one to eleven. There was a significant ($p < 0.001$) positive linear relationship between **YAP** and height (**H**) as expected (Fig. 2). When grouped by vegetation type, willow LSF had a higher R^2 value than conifer at 0.831 and 0.421 (Table 2). **H** of conifer LSF was both higher and lower than willow of equal and similar

YAP. Sardinia-corn-1 had the lowest **H** of any fence. Manheim-honeysuckle-8 had substantially less **H** than willow and conifer LSF of similar **YAP**.

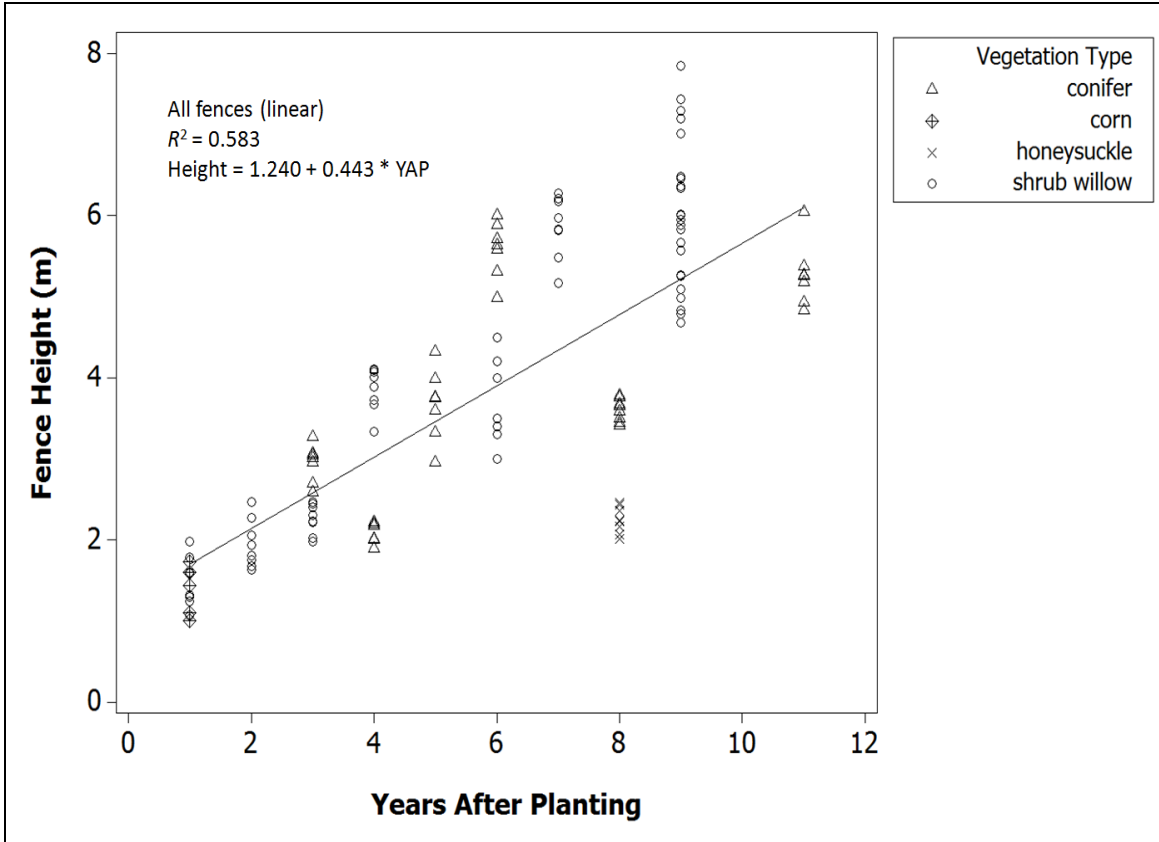


Fig. 2 Years after planting (**YAP**) versus height (**H**) for 18 living snow fences

Table 1 Mean and (standard error) for height, porosity, fetch and setback of 18 living snow fences in New York State

Taxonomy <i>Scientific</i> (common)	Fence ID Tag Town-vegetation-YAP	H	P	F	D
		Height m	Porosity %	Fetch m	Setback m
<i>Salix</i> spp (shrub willow cultivars)	Paris-willow-1	1.5 (0.11)	92 (1.0)	109 (25.0)	26 (3.4)
<i>Salix</i> spp (shrub willow cultivars)	Beerston-willow-2	1.9 (0.11)	88 (1.1)	128 (5.7)	27 (0.3)
<i>Salix</i> spp (shrub willow cultivars)	Hamburg-willow-3	2.3 (0.06)	77 (2.0)	780 (325.1)	28 (1.3)
<i>Salix</i> spp (shrub willow cultivars)	Tully-A-willow-4	3.9 (0.09)	61 (1.6)	750 (36.6)	42 (0.9)
<i>Salix</i> spp (shrub willow cultivars)	Tully-B-willow-6	3.3 (0.07)	61 (2.5)	185 (0.0)	10 (0.0)
<i>Salix</i> spp (shrub willow cultivars)	Tully-C-willow-6	4.2 (0.07)	62 (1.3)	185 (0.0)	10 (0.0)
<i>Salix</i> spp (shrub willow cultivars)	Grand-Gorge-willow-7	5.9 (0.14)	47 (2.7)	171 (25.0)	95 (14.7)
<i>Salix</i> spp (shrub willow cultivars)	Preble-A-willow-9	5.0 (0.08)	33 (3.9)	480 (0.0)	13 (0.0)
<i>Salix</i> spp (shrub willow cultivars)	Preble-B-willow-9	5.9 (0.09)	39 (1.6)	370 (0.0)	10 (0.0)
<i>Salix</i> spp (shrub willow cultivars)	Preble-C-willow-9	7.0 (0.20)	26 (3.5)	538 (0.0)	9 (0.0)
<i>Picea abies</i> (Norway spruce)	Columbia-conifer-3	2.9 (0.08)	27 (3.0)	855 (0.0)	52 (0.0)
<i>Picea pungens</i> (blue spruce)	Chautauqua-conifer-4	2.1 (0.04)	61 (0.5)	620 (0.0)	59 (0.0)
<i>Picea pungens</i> (blue spruce)	Pomfret-conifer-5	3.6 (0.17)	41 (1.7)	437 (0.0)	31 (0.0)
<i>Pseudotsuga menziesii</i> (Douglas fir)	Spencerport-conifer-6	5.6 (0.11)	29 (1.9)	157 (10.7)	37 (0.6)
<i>Thuja occidentalis</i> (white cedar)	Gabriels-conifer-8	3.6 (0.05)	39 (1.3)	470 (59.4)	17 (0.0)
<i>Abies concolour</i> (white fir)	Cobleskill-conifer-11	5.3 (0.13)	38 (3.0)	318 (64.2)	41 (0.6)
<i>Zea mays</i> (corn)	Sardinia-corn-1	1.3 (0.09)	0 (0.0)	340 (0.0)	71 (0.0)
<i>Lonicera tatarica</i> (honeysuckle)	Manheim-honey-8	2.2 (0.06)	63 (2.5)	206 (18.3)	38 (0.3)

Table 2 Regression results for 18 living snow fences of various years after planting (YAP) and vegetation types

Linear	Vegetation Type	DF	p value	R ²	Regression Equation
YAP versus H	all	143	<0.001	0.583	H = 1.240 + 0.443 * YAP
YAP versus H	shrub willow	79	<0.001	0.831	H = 0.864 + 0.575 * YAP
YAP versus H	conifer	47	<0.001	0.421	H = 1.950 + 0.307 * YAP
YAP versus P	all	135	<0.001	0.396	P = 0.630 - 0.025 * YAP
YAP versus P	shrub willow	79	<0.001	0.866	P = 0.994 - 0.073 * YAP
YAP versus P	conifer	47	0.659	-	-
YAP versus Q _c	all	17	<0.001	0.535	Q_c = -42.1 + 36.5 * YAP
Non-linear	Vegetation Type	DF	p value	S	Regression Equation
Q _c /Q versus L	all	17	0.006	4.037	L = 7.693 + 18.884 * exp(-0.192 * Q_c/Q)
Quadratic	Vegetation Type	DF	p value	R ²	Regression Equation
YAP versus L	all	17	<0.001	0.396	L = 32.430 - 6.100* YAP + 0.370²

There was a significant ($p < 0.001$) negative linear relationship between **YAP** and optical porosity (**P**) as expected (Fig. 3). Sardinia-corn-1 was excluded from this regression because **P** was 0% ±0% (non-

porous) one **YAP** making it a distinct outlier. The R^2 of this regression was low at 0.396 due to differences between shrub willow and conifer LSF. **YAP** versus **P** for willow LSF was significant ($p < 0.001$) with an R^2 of 0.866. **YAP** versus **P** for conifer LSF was not significant ($p = 0.659$), indicating that porosity did not change three to eleven **YAP** for this vegetation type. **P** of conifer LSF was generally less than willow LSF of similar **YAP**. **P** of Manheim-honeysuckle-8 was higher (more porous) than willow and conifer LSF of similar **YAP**.

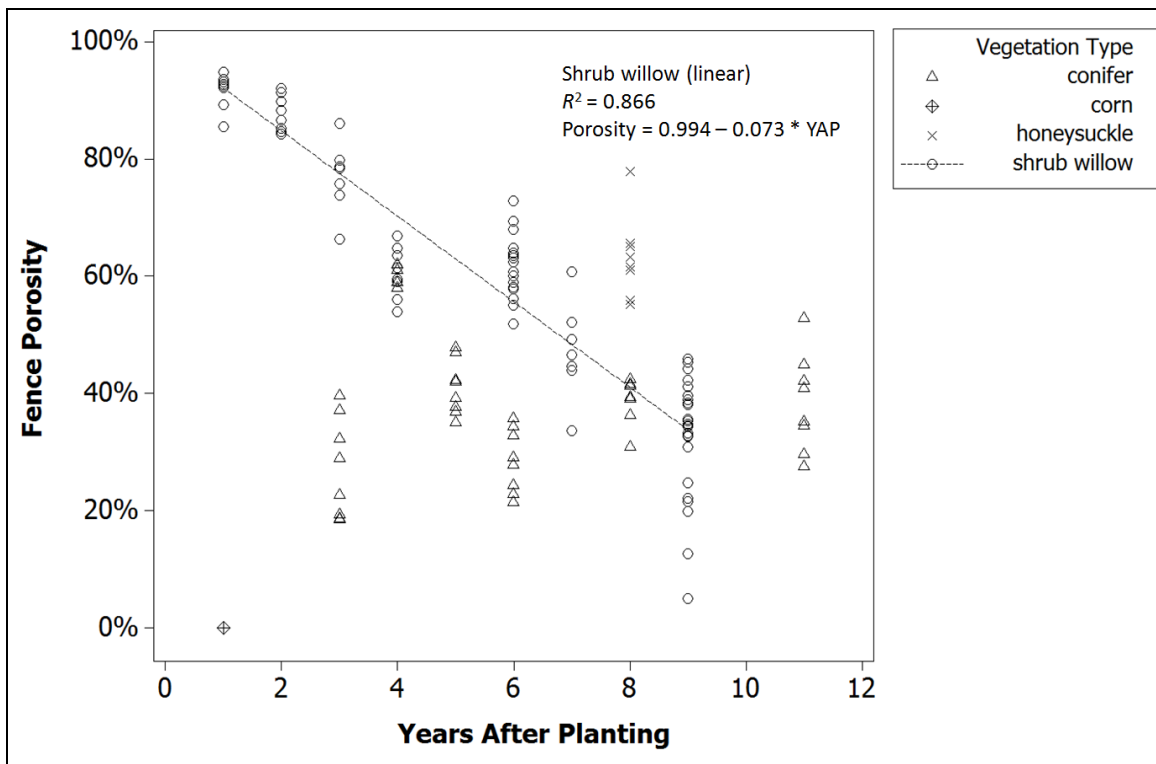


Fig. 3 Years after planting (**YAP**) versus optical porosity (**P**) for 18 living snow fences

Combined **H** and **P** data produced estimated fence capacity (Q_c) ranging from $<1 - 430$ t/m (Table 3). There was a significant ($p < 0.001$) positive linear relationship between Q_c and **YAP** (Fig. 4). Snow transport (**Q**) estimates ranged from 3 - 19 t/m and were substantially smaller than Q_c at most sites creating large capacity/transport ratios (Q_c/Q). Sardinia-corn-1 and willow LSF one and two **YAP** had Q_c/Q less than 1:1. Willow and conifer LSF both had Q_c/Q greater than 1:1 three **YAP**, meaning that

three growing seasons after planting, storage capacity was greater than average annual snow transport.

Shrub willow, conifer and honeysuckle LSF four to eleven **YAP** had Q_c/Q between 3:1 and 110:1.

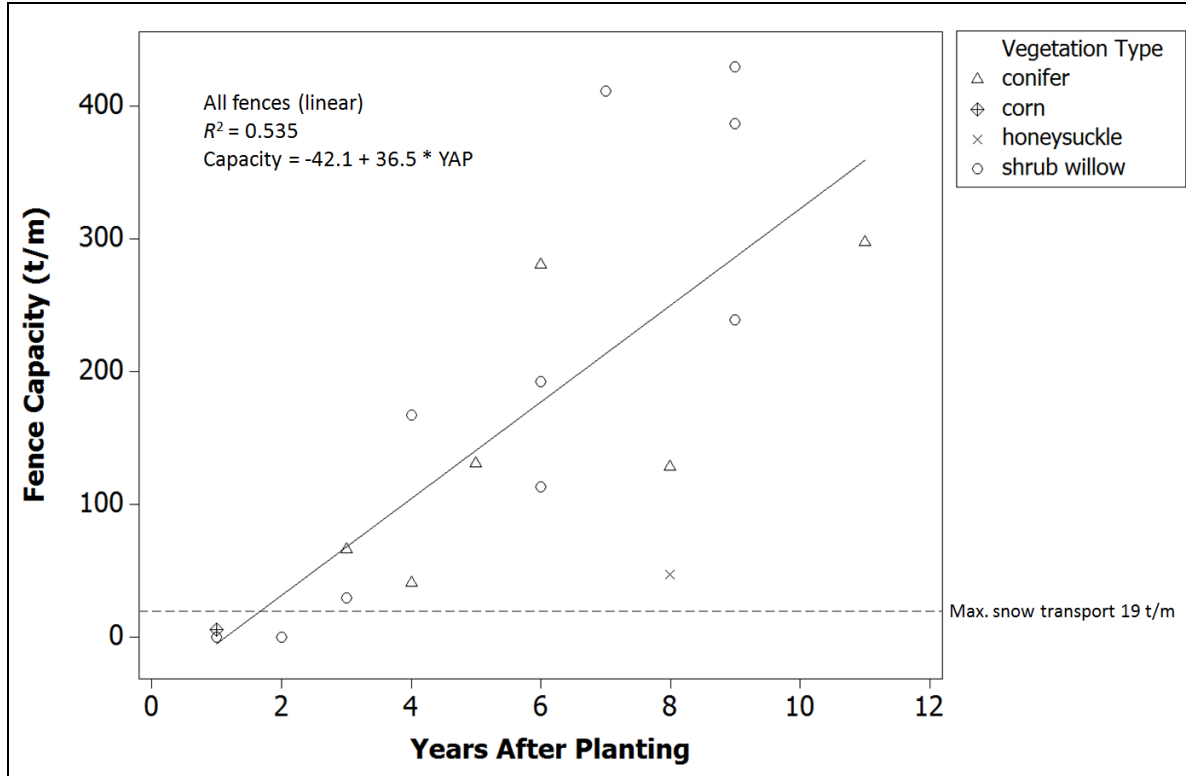


Fig. 4 Fence capacity (Q_c) of 18 living snow fences ranged from 1 - 430 t/m. Capacity exceeded the maximum snow transport (Q) at any site of 19 t/m just three years after planting (**YAP**) and capacity continued to increase in a linear trend four to eleven **YAP**.

Table 3 Estimated snow trapping potential and drift length of 18 living snow fences in New York State ^a

Fence ID Tag	Q_c	Q	Q_c/Q	L	$D35$	$D35/L$
	Fence Capacity t/m	Snow Transport t/m	Capacity/ Transport Ratio x:1	Downwind Drift Length m	Standard Setback m	Standard Setback/ Estimated Drift x:1
Town-vegetation-YAP						
Paris-willow-1	<1	8	<1	34	30	0.9
Beerston-willow-2	<1	3	<1	20	18	0.9
Hamburg-willow-3	29	19	1.5	30	46	1.5
Tully-A-willow-4	167	13	13	13	38	2.9
Tully-B-willow-6	113	4	30	7	22	3.1
Tully-C-willow-6	192	4	50	7	22	3.1
Grand-Gorge-willow-7	411	4	110	7	22	3.1
Preble-A-willow-9	239	7	34	9	33	3.7
Preble-B-willow-9	387	9	44	8	29	3.6
Preble-C-willow-9	430	10	43	8	32	4.0
Columbia-conifer-3	66	15	4	12	41	3.4
Chautauqua-conifer-4	40	12	3	16	37	2.3
Pomfret-conifer-5	130	7	19	9	28	3.1
Spencerport-conifer-6	280	3	82	5	21	4.2
Gabriels-conifer-8	128	17	8	14	43	3.1
Cobleskill-conifer-11	297	8	39	9	30	3.3
Sardinia-corn-1	5	7	<1	18	29	1.6
Manheim-honey-8	47	5	10	8	24	3.0

a: reported Q_c and Q values are rounded to the nearest whole number. Q_c/Q is the rounded ratio of actual Q_c and Q values

There was a significant ($p = 0.006$) asymptomatic relationship between Q_c/Q and L (Fig. 5). Based on the trend of all LSF, Q_c/Q approximately 15:1 or greater was consistently correlated with L values less than 10 m. L ranged from 5 - 34 m with a mean of 13 m. Observed setback (D) ranged from 9 - 95 m with a mean of 34 m. Setback using the standard protocol (D_{35}) ranged from 18 - 46 m with a mean of 30 m.

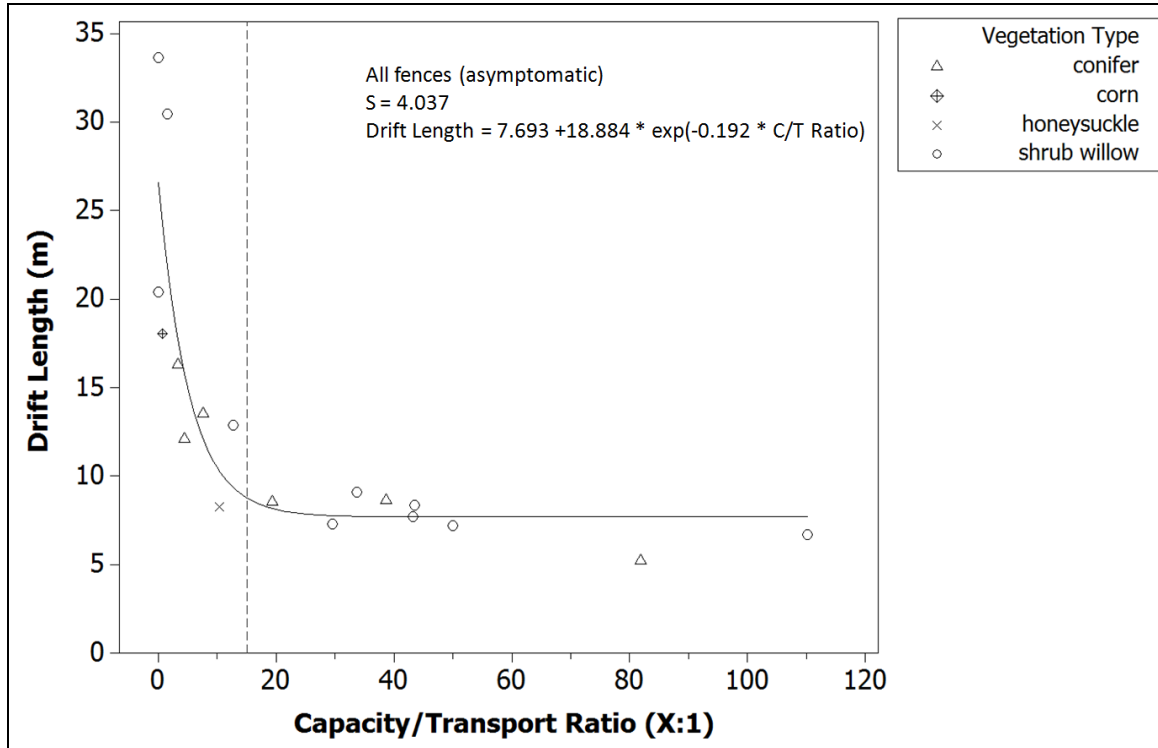


Fig. 5 Capacity/transport ratio (Q_c/Q) versus downwind drift length (L) for 18 living snow fences of various vegetation types and years after planting (YAP). When Q_c/Q exceeds 15:1 the estimated drift length is less than 10 m.

There was a significant ($p < 0.001$) quadratic relationship between YAP and L amongst all LSF (Fig. 6). Drift lengths less than 10 m associated with $Q_c/Q > 15:1$ occurred five YAP and later. L was less than D and D_{35} for 15 of 18 LSF, with newly planted willow LSF being the only exceptions. Dividing the standard setback by estimated drift length (D_{35}/L) showed that the standard protocol for LSF produced setbacks three to four times larger than the estimated drift length for fences four YAP and older (Table 3).

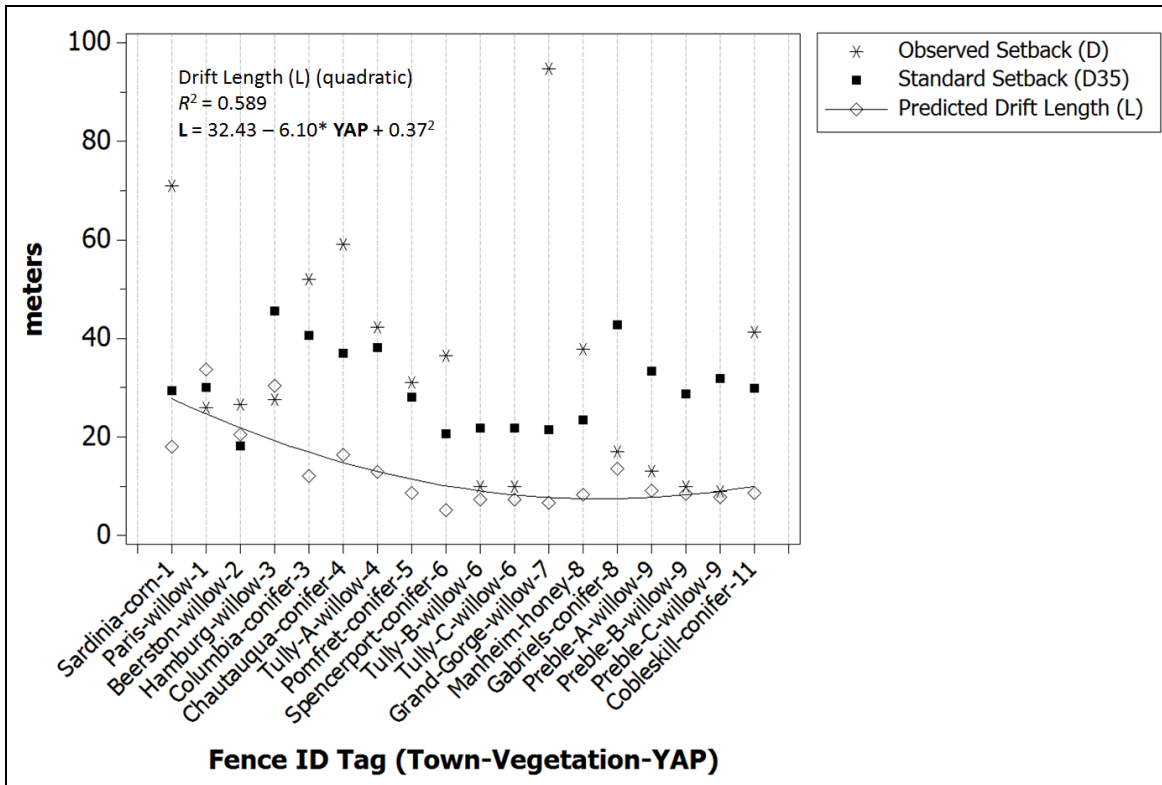


Fig. 6 The standard setback protocol (D35) was three to four times greater than estimated drift length (L) for LSF of various vegetation types in New York State four years after planting and later.

4. Discussion

4.1 Plant Growth and Snow Trapping Potential

Height (**H**) and optical porosity (**P**) are the key plant growth variables influencing snow trapping potential of LSF. The number of years after planting until **H** and **P** are sufficient to create snow trapping capacity (Q_c) greater than snow transport (Q) is an important factor in the functionality and design of LSF. This study showed that **H** and **P** growth of conifer and shrub willow LSF created capacity/transport ratios (Q_c/Q) greater than 1:1 as early as three years after planting (Fig. 7). This confirms previous assessments (Volk et al. 2006; Kuzovkina and Volk 2009) that noted shrub willow’s rapid growth rate and high stem counts should produce snow trapping potential two to three years after planting with proper

establishment. The results of the current study differ from most literature which generally states LSF require five to seven years or longer before snow trapping begins (Tabler 2003; USDA 2011).



Fig. 7 Four years after planting, height (**H**) of living snow fence Tully-A-willow-4 was 3.9 m, porosity (**P**) was 61%, and the resulting estimated snow storage capacity (**Q_c**) was 167 t/m. Average annual snow transport (**Q**) at the site was 13 t/m, creating capacity/transport ratio (**Q_c/Q**) 13:1 and estimated downwind drift length (**L**) of 13 m.

Q_c/Q greater than 1:1 shortly after planting was due to the rapid growth of shrub willow LSF, the use of large (1 - 2 m) planting stock for conifer LSF, and the use of best practices for installation and management. **Q** was less than 20 t/m across all sites - classified as “very light” (<10 t/m) or “light” (10 - 19 t/m) blowing snow conditions by Tabler (2003). Higher **Q** combined with slower growing plants, smaller planting stock, or a lack of best practices would increase the amount of time for **Q_c/Q** to exceed 1:1. Powell et al. (1992) reported an extreme case in which LSF in Wyoming required 20 years before

becoming fully effective in snow transport conditions of approximately 100 t/m. However, willow and conifer LSF four and five **YAP** had $Q_c > 100$ t/m in the current study, and eight LSF had Q_c sufficient for “severe” conditions up to 320 t/m (Tabler 2003). This indicates that with proper plant selection and other best practices, Q_c/Q can exceed 1:1 creating snow trapping potential several years earlier than commonly reported, even on sites with higher snow transport. The use (or lack) of best practices is a critical factor influencing the number of years required for Q_c/Q to exceed 1:1. This includes a comprehensive suite of practices starting with site assessment through post-installation monitoring and maintenance (see Gullickson et al. 1999; Tabler 2003; Heavey and Volk 2013). Numerous LSF where best practices had not been employed were observed during the site selection phase of this study and the stunted growth and high mortality that resulted did not create height or porosity adequate for substantial trapping potential.

Shrub willow LSF managed using best practices may improve the function and economic efficiency of LSF due to unique plant characteristics that continue to be developed through breeding programs for woody biomass production and alternative applications (Volk et al. 2006; Smart and Cameron 2008; Serapiglia et al. 2012). The cost of willow LSF is low relative to other vegetation types because willow can be propagated from unrooted stem cuttings inserted into properly prepared ground at high planting densities. The estimated cost of installation *and* maintenance of a shrub willow fence in average site conditions is approximately \$20,000/km (Heavey and Volk 2012). By comparison, Walvatne (1991) reported the cost of installation contracts for LSF of other vegetation types in Minnesota between \$53,000/km and \$212,000/km (2013 US\$). Other contracts for LSF have been reported at \$25,000/km in Iowa (Shaw 1989), and \$38,000/km in Colorado (Powell et al. 1992) who also reported the cost of “Wyoming” style structural snow fences 4.3 m in height to be \$68,000/km. Willow showed more consistent **H** and **P** trends than conifer LSF, which may allow for more exacting design, but the willow LSF investigated had design input from one or both authors creating consistency of management practices which may account for some of the predictability. Conifer LSF were located in multiple regions under the

care of various local transportation residencies and different management practices which would contribute to more inconsistent patterns of development.

The one corn fence investigated had Q_c/Q less than 1:1 due to small H (1.3 m) caused by the maximum of one growing season for this annual vegetation type and wet snow that broke off the tops of the plants, a phenomenon also observed by Shulski & Seeley (2001). The multiple rows of corn left standing also resulted in 0% P , which further reduces Q_c . The honeysuckle fence investigated had Q_c/Q of 10:1 eight YAP , but less Q_c than willow and conifer LSF of similar YAP . The honeysuckle plant morphology created a large bottom gap in the fence which likely allows some amount of snow to blow through the fence without being trapped. Overall, the large Q_c/Q soon after planting for most fences in this study has important implications for the function and design of LSF. Q_c/Q greater than 1:1 causes drift growth to terminate prior to maximum equilibrium length ($35H$), resulting in reduced drift lengths and setback requirements.

4.2 Drift Length and Setback

The selection of setback distance for LSF is complicated by the fact that plants grow over time. Setback distance should accommodate the entire length of the downwind drift but not be excessively large. When LSF grow to large heights, Q_c/Q can substantially exceed 1:1 and the length of the downwind drift and required setback distance are reduced. Tabler's (2003) standard setback protocol for LSF (**D35**) slightly modifies the protocol established for structural snow fences ($35H$), but does not fully account for increasing Q_c/Q over time. Drift formation around LSF occurs in stages over the course of a drift accumulation season as wind turbulence and drift growth alternates between the upwind and downwind side of the fence (Tabler 2003). As these alternating stages progress and the quantity of snow in the drift increases, height of the snow drift at first increases faster than the length of the drift. Once drift height reaches the approximate height of the fence in the early stages of formation, drift length then

begins to extend further downwind from the fence toward the road. The Q_c/Q values much larger than 1:1 estimated in this study cause drifts to terminate in the early stages of formation when downwind length is only a fraction of the maximum $35H$ (Tabler 2003). The greater the Q_c/Q , the shorter drift length will be because the fence only fills to a small percentage of its maximum snow holding capacity (Tabler 2003).

Based on the output of estimated drift length (L) for the fences investigated in this study, when Q_c/Q is greater than 15:1, L is consistently less than 10 m, which occurred five **YAP** and later. This correlation between drift length and capacity/transport ratio is likely synonymous with the first stage of drift formation before the drift builds to the height of the fence and begins to extend downwind toward the road [see Tabler (2003) and Heavey (2013) for a more in-depth explanation of drift growth dynamics]. Quantitative design protocols that account for changing capacity and drift length over time have not been integrated into extension publications and the L values in this study are expectedly less than observed setback distances (D) and calculated setbacks using the standard protocol (**D35**). **D35** was three to four times larger than L for LSF four **YAP** and older and D was even larger in most cases. Several of the willow LSF designed with input from the authors had setback distances much closer to the predicted drift length and have been reported effective by transportation staff in mitigating blowing snow problems since being installed, but setbacks of many LSF in the field are substantially larger than necessary. While extensive information and protocols for quantifying and selecting setback distances exist for structural snow fences, similar protocols for LSF are more complicated and less complete (Nixon et al. 2006), but are currently being developed (Heavey and Volk 2013).

Setback of structural snow fences is selected using Tabler's (2003) $35H$ and modifications to this protocol. Key assumptions of $35H$ are that fences are constructed to known height and porosity specifications that create capacity equal to or greater than snow transport; and fence capacity does not change over time. $35H$ has been mistakenly applied to the anticipated *mature* height of LSF, disregarding the impact of capacity/transport ratio and creating setback distances far too large. Tabler (2003) and a

limited number of other publications (Blanken 2009) provide a slightly modified version of 35H with the **D35** protocol, in which $D35 = 35H_{req}$. Using H_{req} instead of mature height reduces setback based on snow transport, but does not account for changes in Q_e/Q over time. Most extension and other publications aimed at selecting appropriate setback for LSF are vague and inaccurate. These sources provide broad ranges and excessively large recommendations (30 - 185 m) with little or no quantitative protocols (Table 4).

Table 4 Setback recommendations for LSF from various publications are often broad ranging, excessively large and not supported by quantitative protocols

Source	Setback Recommendation	Quantitative Protocol
Heavey and Volk (2013)	Estimated drift length in chosen design year	Yes
CSU Extension (2013)	>60 m	No
NYSDOT (2012)	30 – 60 m	No
USDA (2011)	30 – 185 m	No
CCE (2011)	60 – 90 m	No
Blanken (2009)	$35H_{req}$	Yes
Barkley (2008)	>30 m	No
Bratton (2006)	45 – 75 m	No
SDDA (2004)	>50 m	No
Josiah and Majeski (2002)	Not specified	No
Shulski and Seeley (2001)	$D = H (\sin \alpha) (12 + 49P + 7P^2 - 37P^3)$	Yes
Streed and Walton (2001)	30 – 150 m	No
Gullickson et al. (1999)	$L/H = (12 + 49P + 7P^2 - 37P^3)$	Yes
Shaw (1989)	>60 m	No
Shaw (1988)	Not specified	No

The current study offers potential for improved quantitative design protocols, but the estimated Q_e/Q and L values produced should be validated with future research that measures snow drifts around LSF in the field. This was originally planned for the current study but was unable to be completed due to frequent warm ups and rain events during the winter of 2012/2013 that negated any substantial drift growth. If validated, Tabler’s (2003) L model or the **YAP** versus L regression equation produced in this study can be used to estimate required setback based on drift length in any chosen “design year”. This allows drift length in various years after planting to be modeled to inform the design process. An appropriate design year and corresponding setback distance can then be selected, taking into consideration site specific

factors, knowledge of the chosen plant species, and the long term snow control goals for the site. For example, if a shrub willow fence on a given site is expected to have capacity/transport ratio of 20:1 five years after planting, and the corresponding drift length is estimated at 8 m, a setback of 12 m might be considered acceptable and selected in order to locate plants on the far edge of the transportation right of way and ensure that drifts around the fence do not encroach on the roadway. In the years prior to the fence reaching 20:1 Q_c/Q , traditional snow controls would still be required and temporary (plastic) snow fences could be installed upwind of the living fence to mitigate the possibility of the drift extending onto the roadway. This approach could potentially accommodate LSF installations on many sites where blowing snow problems exist but planting space is limited due to right of way constraints or other planting limitations. The selection of setback distance should be as precise as possible (neither too large nor too small) to accommodate the entire length of the downwind drift, reduce the possibility of “near-snow problems” between the fence and road, and avoid unnecessary land acquisitions for additional planting space.

An important factor when considering reduced setback distances is exceedance probability, or the chance that snow transport will exceed fence capacity and/or create a longer than anticipated drift length in winters with above average snow loads or prior to the fence achieving a large Q_c/Q . If Q_c/Q substantially exceeds 1:1, a fence is unlikely to fill to capacity even in the most extreme winters, but drift length may still exceed predicted L . The probability of a drift accumulation season in which Q is twice the average is less than 0.1% (Tabler 2003). Q_c/Q of 2:1 would therefore have sufficient capacity for this rare scenario and LSF with Q_c/Q greater than 2:1 would have a reduced drift length. Similarly, the snow relocation coefficient (C_r) of 0.17 assumed for every site in this study could be higher at any given site or even double the assumed value as estimated at 0.35 in Shulski and Seeley (2001), which may increase the number of years until Q_c/Q exceeds 1:1 and drift length is reduced. Hypothetically doubling C_r for every site in the current study would double the Q value at all sites and reduce Q_c/Q by half, but willow and conifer LSF would still have $Q_c/Q > 1:1$ four years after planting, and 4:1 to 54:1 five to eleven years after

planting. In general, large amounts of excess storage capacity soon after planting appear to mostly offset the potential impacts of above average winters and lessen the importance exceedance probabilities. Continued testing and refinement of these scenarios and design protocols is a pertinent area of future research, in conjunction with field studies to validate models of plant growth, snow storage capacity and drift length.

5. Conclusion

LSF can reduce the cost of snow control and improve highway safety by trapping blowing snow in drifts before it reaches the road, providing economic, social and environmental benefits. The key plant growth variables for snow trapping of height (**H**) and optical porosity (**P**) were measured on 18 LSF of various vegetation types and years after planting. **H** increased linearly over time and **P** decreased linearly for willow LSF, but did not change for conifer LSF. Three years after planting, conifer and willow LSF had capacity/transport ratios (Q_c/Q) greater than 1:1, indicating snow trapping potential sooner than reported in most publications. The use of best practices is critical in creating this early snow trapping potential. Four to eleven years after planting, Q_c/Q was between 3:1 and 110:1 indicating large excess storage capacity relatively early in the potential life cycle of the fences. Doubling the estimated snow transport did not substantially reduce the large amounts storage capacity, indicating that these results are applicable to a wider geographic area than New York State where snow transport conditions may be higher. Estimated drift length (**L**) was consistently less than 10 m when Q_c/Q exceeded 15:1. This occurred five years after planting and is much smaller than most setback distances observed in the field and recommended in current publications. The results of this study can improve quantitative design protocols for LSF making fences more effective and facilitating installations on more sites through reduced setback distance based on estimated drift length. Future research should seek to validate estimates of Q_c/Q and **L** with field measurements and incorporate research results into extension publications for the improved design, function and adoption of LSF.

Acknowledgements

This research was funded by the New York State Department of Transportation (NYSDOT) and the United States Department of Transportation (USDOT) Research and Innovative Technology Administration (RITA) as part of University Transportation Research Center (UTRC) Project C-06-09: “Designing, Developing, and Implementing a Living Snow Fence Program for New York State”. This research was made possible through the support and assistance of countless staff at the New York State Department of Transportation (NYSDOT) and colleagues at the State University of New York - College of Environmental Science and Forestry (SUNY-ESF).

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Appendix B – Structure and Function of LSF in New York State

STRUCTURE AND FUNCTION OF LIVING SNOW FENCES IN NEW YORK
STATE

by

Justin P. Heavey

A thesis
submitted in partial fulfillment
of the requirements for the
Master of Science Degree
State University of New York
College of Environmental Science and Forestry
Syracuse, New York
August, 2013

Approved: Department of Forest and Natural Resources Management

Timothy Volk, Major Professor

John Hassett, Chair
Examining Committee

David Newman, Department Chair
Forest and Natural Resources Management

S. Scott Shannon, Dean
The Graduate School

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Acknowledgments

I acknowledge and thank everyone at the State University of New York College of Environmental Science and Forestry for being part of this wonderful institution that has been the platform of my graduate education and research. Specifically I thank Dr. Timothy Volk for serving as my major professor, providing me with many opportunities, and supporting my interest in living snow fences. I thank all the professors at ESF who have passed on their knowledge, skills, and passion for environmental education, research, and stewardship. I thank all of my colleagues from the Willow Project at SUNY-ESF who assisted me with various aspects of this project, and my fellow students who traveled with me to snow fence sites all over the state collect the data for this project. I thank John Rowen and all of his colleagues in the New York State Department of Transportation for their willingness to deploy living snow fences on New York's roadways, support the research and development of living snow fences, and for providing key information and assistance which made this project possible. I acknowledge and thank the late Ronald Tabler who was a pioneer in structural and living snow fences. I also thank my family and friends for everything they have done for me throughout my life.

Disclaimer

The contents of this paper reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. Portions of this paper have been derived from information obtained during a research project C-06-09 “Designing, Developing, and Implementing a Living Snow Fence Program for New York State” conducted through the State University of New York College of Environmental Science and Forestry. Such research project was funded in whole or in part by the New York State Department of Transportation and/or the Federal Highway Administration. The final results of such research project have not been approved by the Department of Transportation and or the Federal Highway Administration as of the date of this writing. The contents do not necessarily reflect the official views or policies of the New York State Department of Transportation, or the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

List of Symbols

Symbol	Meaning	Unit
H	Height of a living snow fence	m
P	Optical porosity of a living snow fence	%
Q	Average annual quantity of snow transport at a snow fence site	t/m
F	Fetch distance	m
C_r	Relocation coefficient, fraction of fallen snow relocated by the wind	none
H_{req}	Required fence height	m
Q_c	Snow storage capacity of a fence	t/m
Q_c/Q	Capacity/Transport ratio of a fence	none
α	Angle of the prevailing winter wind relative to the road area needing protection	°
L	Length of the downwind drift of a snow fence	m
A/A_e	Ratio of the pre-equilibrium drift area (A), to the area that would be occupied by equilibrium drift (A_e), when fence capacity exceeds transport	none
S_{we,AS}	Water equivalent of snowfall over the drift accumulation season	m
D	Observed setback distance of a snow fence	m
D₃₅	Predicted setback of a living snow fence, approximately 35 times the required fence height	m

List of Models and Equations

Number	Model Description	Equation	Source
Equation 1	Equilibrium drift length	$L/H = 12 + 49P + 7P^2 - 37P^3$	Tabler (2003)
Equation 2	Pre-equilibrium drift length	$L/H = 10.5 + 6.6(A/A_e) + 17.2(A/A_e)^2$	Tabler (2003)
Equation 3	Living snow fence drift length	$L/H = ([10.5 + 6.6(A/A_e) + 17.2(A/A_e)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)$	Tabler (2003)
Equation 4	Average annual snow transport	$Q = 1500(0.17)(S_{we,AS})(1-0.14^{F/3000})$	Tabler (2000)
Equation 5	Snowfall water equivalent over the accumulation season	$S_{we,AS} = (-695.4 + 0.076 * Elev + 17.108 * Lat)(0.10)$	Tabler (2000)
Equation 6	Snow storage capacity of a fence	$Q_c = (3 + 4P + 44P^2 - 60P^3) H^{2.2}$	Tabler (2003)
Equation 7	Capacity/Transport ratio of a fence	Q_c/Q	Current Study
Equation 8	Required height of a fence	$H_{req} = (Q/8.5)^{0.455}$	Tabler (2003)
Equation 9	Predicted setback of a living snow fence	$D_{35} = (\sin\alpha)35H_{req}$	Tabler (2003)
Equation 10	Length of downwind drift model 1	$L = ([10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)(H)$	Tabler (2003)
Equation 11	Length of downwind drift model 2	$L = ([10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)(H_{req})$	Tabler (2003)

Abstract

J. P. Heavey. Structure and Function of Living Snow Fences in New York State, 133 pages, 9 tables, 49 figures, 2013.

This study investigated 18 living snow fences of various ages and species in New York State. Key structural variables of fence height and optical porosity were measured and modeled to estimate the snow trapping function of each fence in terms of snow storage capacity, capacity/transport ratio, and drift length. Height increased linearly over time and porosity decreased linearly over time. Three years after planting, height and porosity was sufficient to create fence capacity that exceeded the average annual snow transport at each site, earlier than what is often reported in the literature. For fences age five and older, capacity/transport ratios were between 8:1 and 110:1, indicating large amounts of excess storage capacity. The model of downwind drift length showed that when capacity/transport ratio exceeds 15:1, setback distance can be 10 m or less, much smaller than what is recommended in the literature and setback distances observed in the field.

Key Words: agroforestry, optical porosity, setback, windbreaks, shelterbelts, transportation, green infrastructure, shrub-willows, *Salix*, snow drifts, snow hydrology, passive snow control, blowing snow, snow and ice control, highway maintenance, highway safety, roadside vegetation, right of way vegetation, sustainable vegetation systems, NYSDOT, ecological engineering, blowing and drifting snow

J. P. Heavey

Candidate for the degree of Master of Science, August, 2013

Timothy A. Volk, Ph.D.

Department of Forest and Natural Resource Management

State University of New York College of Environmental Science and Forestry

Syracuse, NY

Timothy A. Volk, Ph.D. _____

1 INTRODUCTION

The occurrence of blowing and drifting snow on roadways can increase the cost of highway maintenance and create hazardous driving conditions (Tabler 2003). Blowing and drifting snow problems on roadways can occur when snow is lifted off the ground by the wind and transported across an open area towards a road. If snow transport is not disrupted by a physical structure or topographical feature before it crosses or comes into close proximity with the road, blowing snow problems are likely to occur.

Local and state agencies in the United States spend over \$2 billion annually on snow and ice control operations, and an additional \$5 billion annually to repair infrastructure damaged by snow and ice (NCHRP 2005). In New York State, The Department of Transportation (NYSDOT) is responsible for snow and ice control on 43,000 lane miles of highway; maintained by a fleet of over 1,400 large plow trucks, 326 loaders, 50 snow blowers, and 3,300 operators; using over 800,000 tons of salts and abrasives; and over 700,000 gallons of de-icing liquids annually (Lashmet 2013). The combined cost of equipment, labor, materials, fuel, and sub-contracts to achieve this level of snow and ice control is over \$300 million annually (Lashmet 2013). Living snow fences are a best management practice for snow and ice control (Lashmet 2013, Goodwin 2003) that can mitigate blowing snow problems, partially reduce the costs of highway maintenance, and improve highway safety.

Living snow fences are an agroforestry practice similar to windbreaks or shelterbelts (USDA 2012). Living snow fences are intentionally planted rows of vegetation that perform the same function as *structural* snow fences, such as wooden, plastic, or metal fences. Living snow fences

disrupt wind patterns and create wind turbulence and eddies around the fence, causing snow to be deposited in designated areas before it reaches the roadway (Tabler 2003). Living snow fences can consist of any tree, shrub, or grass species, or any combination of species which meets the traits required for snow trapping, including sufficient height, sufficient optical porosity, a ground level branching pattern, an absence of self-pruning characteristics, and sufficient growth rates. Living snow fences of various species have been planted in New York State over the past decade and longer by NYSDOT, and more recently by the State University of New York - College of Environmental Science and Forestry (SUNY-ESF), in collaboration with NYSDOT.

This thesis was an observational study of living snow fences of various ages (years since planting) and species in New York State. The objectives of this study were to:

1. Select a stratified sample of the statewide living snow fence population for study.
2. Measure the key structural variables of height and optical porosity at each fence.
3. Model structural data to estimate the snow trapping function of fences in terms of snow storage capacity, capacity/transport ratio, and predicted length of the downwind drift.
4. Test for significant relationships between the predictor variable of fence age (years since planting), and the response variables of fence height, porosity, and capacity.
5. Evaluate and compare estimates of fence snow storage capacity, relative to the estimated snow transport quantities at each site.
6. Evaluate the influence of capacity/transport ratios on the predicted length of the downwind snow drift.
7. Discuss results in context of current literature and design standards of living snow fences.

2 LITERATURE REVIEW

2.1 Economic, Safety, and Environmental Benefits of Living Snow Fences

Living snow fences are rows of densely planted trees, shrubs, or other vegetation installed along roadways for the purpose of mitigating blowing and drifting snow problems. The goal and function of living snow fences is the same as structural snow fences; to act as a semi-porous barrier that disrupts wind-driven snow transport and causes snow deposition in designated areas, both upwind and downwind of the fence (Tabler 2003). Inducing controlled snow deposition in drifts before it reaches the roadway with living snow fences can reduce the cost of highway maintenance by reducing the need for mechanical and chemical snow and ice control, and reducing damage to roadways caused by snow and ice (Tabler 2003).

Living snow fences are capable of reducing the costs associated with controlling blowing snow problems by over 90% (Tabler 2003). This corresponds to the maximum snow trapping efficiency of living snow fences which is also approximately 90% (Tabler 2003). Unlike structural snow fences, *living* snow fences require a number of years after planting to grow and become fully functional. A “fully functional” living snow fence in this study refers to a fence that has snow storage capacity which is equal to, or greater than, the average annual snow transport at the snow fence site. Living snow fences may have higher initial costs than structural snow fences, mainly as a result of installation and maintenance costs until plants become established. However, living fences can have functional service lives that exceed the life cycle of structural fences by 25 years or more (Powell et al. 1992), with little required maintenance after plants become established, potentially offsetting higher initial costs and the time lag between installation and snow trapping function. Living snow fences therefore have the potential to be more economically efficient than structural snow fences. Daigneault and Better

(2000) estimated the life cycle economic performance of “Wyoming” structural snow fences, slatted snow fences, and living snow fences; and reported benefit-cost ratios of 2.4, 2.0, and 5.7 respectively, with the living snow fences also producing a positive net present value.

In addition to reducing the costs of snow and ice control, living snow fences can improve highway safety. Blowing snow can create road safety hazards including snow deposition on the roadway, the formation of ice on the roadway, and reduced visibility for drivers. Tabler and Meena (2006) provided results from a 34 year study in Wyoming that demonstrated a 75% reduction in crash rates in areas protected by snow fences through the reduction of snow and ice accumulation on the roadway and improved visibility. The average financial cost associated with one fatal car accident is approximately \$3.5 million; the cost associated with one injury inducing car accident is \$93,500; and \$5,200 for accidents involving property damage only (NYSDOT 2010a). This represents a compelling case for the use of living snow fences if any of these financial costs, or loss of invaluable human life and wellbeing, can be avoided.

Living snow fences can produce further safety and economic benefits in the form of value travel time savings (VTTS), if driving conditions are improved. Blowing snow problems can cause reduced speeds, and in severe cases, extended road closures (Tabler 2003). Road closures as a result of blowing snow have been documented in several location in the mid-western United States (Tabler 2003), as well as in New York State where road closures from blowing snow can sometimes occur several times per year in certain areas, and last for several hours per event while plow trucks, loaders, and other heavy equipment is used to clear the road (personal communication with M. Murphy, NYSDOT 2012). The average value of car travel time in

2013 dollars is approximately \$15 per hour, and the average value of truck travel time is \$24 per hour (USDOT 2003).

Living snow fences are considered a “green” approach to snow control (Lashmet 2013) that can simultaneously provide numerous environmental benefits such as erosion control, the use of native plants, and carbon sequestration (Gullickson et al. 1999). In addition to carbon sequestration and storage by vegetation, living snow fences have the potential to reduce the use of diesel fuel consumed during snow and ice control operations, further contributing to the likelihood of a carbon negative life cycle for most living snow fences. Living snow fences can provide a suite of other environmental benefits commonly associated windbreaks and shelterbelts such as improved crop yields; shelter for livestock and homes; improved water quality; ornamental/aesthetic value; noise, visual, and odor screens; wildlife habitat (including critical habitat for rare and endangered species); air quality; phytoremediation; and opportunities for environmental education and research (NRCS 2012). Additionally, living snow fences can produce value-added agroforestry crops such as edible fruits and nuts, and other plant products (Streed and Walton 2001). The ability of living snow fences to achieve high levels of environmental performance is supported by NYSDOT’s environmental certification program “GreenLITES”; a self-certification program that evaluates and ranks transportation projects on the use of best practices for environmental sustainability and stewardship (NYSDOT 2010b). Living snow fences are eligible for a high percentage of credits within the GreenLITES certification program (Heavey and Volk 2013a). In order for living snow fences to produce environmental, economic, and safety benefits, fences must be properly designed, installed, and maintained, allowing them to grow into a mature state that induces the intended snow trapping.

2.2 Function of Living Snow Fences

The basic function of living snow fences is summarized here by introducing and defining the terminology and symbols used in the current literature and this study. This terminology is based primarily on Tabler (2003) which is considered the most comprehensive work on both structural and living snow fences to date, as well as Tabler (2000) which provides pertinent climatic data and models that are specific to the design and analysis of snow fences in New York State. Some terms and equations have been slightly modified from their original notation or use for clarity in the current study. Where this is the case, it is noted in this section and further explained in Chapter 3 as necessary.

The two most important structural variables influencing the snow trapping function of living snow fences are fence height (**H**), and optical porosity (**P**) (Tabler 2003). *Structural* snow fences can be designed and built to any height and porosity specifications, and these specifications do not change over time. In the case of *living* snow fences, height and porosity is dictated by the plant species selection, and the planting pattern of the fence (plant spacing, number of rows, and row spacing). Plant morphology changes as fences grow, causing the fence height, porosity, and snow trapping function to shift over time. *Height* in this study is the vertical distance in meters from the ground to the top of the vegetation. Actual height might differ from “effective height” if the porosity of a snow fence is not consistent from top to bottom (Tabler 2003), but this potential distinction was not investigated or differentiated in the current study.

Optical porosity (**P**) is the percentage of open frontal area (area not occupied by any plant parts) when the fence is viewed at a perpendicular angle in winter. Porosity is measured and

reported as a percentage of total frontal area. A fence with 50% porosity is half open space and half “closed” space occupied by vegetation. Percent porosity is the inverse of the vegetation “density”. A fence with 25% porosity would have 75% density, and a fence with 0% porosity would have 100% density, in other words, a completely non-porous (solid barrier).

Snow transport (Q) is the average annual quantity of snow that is transported by the wind towards the road at a living snow fence site. The variable **Q** is measured in units of “t/m”, or metric tons of snow water equivalent per linear meter of fence. Snow transport is primarily a function of *fetch distance (F)* and *relocation coefficient (C_r)*. Fetch (**F**) is the distance in meters from the fence to the first obstruction upwind that disrupts wind patterns and causes snow deposition, such as building or forest. Fetch is thus a measurement of the length of open area contributing to a blowing snow problem. Relocation coefficient (**C_r**) is the estimated fraction (expressed as a decimal) of snowfall lifted off the ground and relocated (transported) by the wind. *Storage capacity (Q_e)* is the quantity of snow a fence can store per linear meter of fence, measured in units of t/m. Storage capacity is a function of fence height and porosity.

Required height (H_{req}) is the estimated height in meters, of a fence with 50% porosity, that would be required to store a designated snow transport quantity (**Q**). In Tabler (2003), the snow transport quantity associated with **H_{req}** can be either **Q** (the average annual transport), or a different quantity of snow transport associated with a chosen “design transport” to account for the probability of years with above average snow transport. For clarity in the current study, **H_{req}** refers *only* to the height required to store the annual average transport quantity (**Q**).

Setback (D) is the distance in meters from the edge of the roadway to the fence. Setback is primarily determined based on the estimated *length of the downwind drift (L)* that will occur on the snow fence. The length of the downwind drift is a function of height, porosity, and the capacity/transport ratio (Q_c/Q) of the fence. Attack angle (α) is the angle of the predominant winter wind relative to the roadway needing protection, which can factor into the calculation of *predicted setback distance (D₃₅)*. Predicted setback (**D₃₅**) is a model from Tabler (2003) that provides a conservatively large estimate of the required setback distance for living snow fences.

2.3 Setback of Living Snow Fences

Selecting a setback distance is an important decision in the design of living snow fences. There is currently no consensus in the literature on how to properly and precisely calculate or select a setback distance for living snow fences. As with *structural* snow fences, the primary factor influencing the decision of setback distance for living fences is the estimated length of the downwind drift (**L**) that will extend from the fence (Tabler 2003). Setback should provide adequate area to accommodate the *entire* length of the downwind drift, so that snow drifts formed around the fence do not encroach on the roadway at any point during the drift accumulation season. A setback distance that is *smaller* than necessary can fail to sufficiently mitigate blowing snow problems, or *exacerbate* problems by causing drifts formed around the fence to encroach on the roadway. Setback distances *larger* than necessary can create “near-snow” problems in which snow on the downwind side of the fence is picked up by the wind and transported towards the roadway (Tabler 2003). Setbacks larger than necessary can also require planting the snow fence beyond transportation agency right of ways, potentially increasing the cost and time of living snow fence installations, or making projects unfeasible in many locations

where blowing snow problems exist but additional right of way space, land leases, or easements cannot be acquired.

Setback distance of snow fences is generally selected using the “standard setback” approach developed by Tabler (2003), based on the estimated length of the downwind equilibrium drift. The distance between the fence and the road that is necessary to accommodate the downwind drift can be calculated from the known patterns of snow drift formation that result when wind transported snow encounters a barrier (fence) of a given height and porosity (Tabler 2003). When designing a snow fence, the design team may choose to calculate drift length and required setback distance based on the average annual snow transport quantity (Q), or a chosen “design transport” that is some multiple of the average transport such as $2Q$, representing a calculated exceedance probability for winters with above average snowfall (Tabler 2003). Once a Q value has been chosen, a setback distance can be determined based on the estimated drift length that will form around the fence at the chosen quantity of blowing snow, and the corresponding estimate of required fence height (H_{req}) (Tabler 2003).

The “standard approach” generally calls for a snow fence with a height that creates storage capacity equal to or greater than the design transport. Once the design transport is determined and the required fence height (at 50% porosity) is calculated, a setback distance is calculated based on the length of the equilibrium (full capacity) drift that will form around the fence. The setback distance necessary to accommodate an equilibrium drift is approximately “ $35H$ ”, or 35 times the height of the fence (Figure 1) (Tabler 2003). A key assumption of the standard setback approach is that the fence, in some or most winters, will fill to the maximum snow

holding capacity creating an “equilibrium” drift around the fence, in which no more snow can be held and wind and snow again flows smoothly over the fence and the drift.

The standard setback approach was developed by Tabler (2003, 1997, 1994, and prior) primarily for the design of *structural* snow fences. However, this approach has often been loosely applied to *living* snow fences in the literature (see Gullickson et al. 1999, Josiah and Majeski 2002, and Blanken 2009). The standard setback approach alone is not an appropriate design standard for living snow fences because the height, porosity, snow trapping function, and drift length of living snow fences changes over time as fences grow. Height of living snow fences generally increases with time, often far exceeding the estimated required height (H_{req}), and porosity generally decreases with time (Tabler 2003). The storage capacity of living snow fences generally increases in response to increasing height, slightly modified by the percent optical porosity (Tabler 2003).

A living snow fence with 50% porosity has the highest amount of snow storage capacity. Fences with porosity greater than 50% have less storage capacity, and fences with porosity greater than 75% are mostly ineffective at trapping snow (Tabler 2003). Fences with porosity less than 50% also have reduced storage capacity, but cause a higher percentage of snow to be stored on the *upwind* side of the fence as porosity declines, shortening the length of the downwind drift (Tabler 2003). The interplay between height, porosity, capacity/transport ratio, and the shifting structure and function of living snow fences over time complicates the task of calculating and selecting an appropriate setback distance. These complexities and nuances

necessitate a more exacting methodology than the standard setback approach (35H) that is often recommended in the literature.

Tabler (2003) provides the most comprehensive discussion and methodology of calculating setback distances for living snow fences, acknowledging the need to address the time sensitive dynamics of living snow fences:

“Guidelines for structural fences also apply to living barriers, but modifications are necessary to take into account the changes in height and porosity as the plants grow. The length of the downwind drift changes with time, and depends on the storage capacity relative to seasonal snow transport.”

The key information in this quote is that *the drift length of living snow fences is dependent on the storage capacity relative to seasonal snow transport*. To illustrate this key concept, Tabler (2003) refers to Figure 1. Note the indication of capacity/transport ratio (Q_c/Q) on the right side of each illustration within Figure 1. As living snow fences grow and mature over time, their snow storage capacity (Q_c) often exceeds snow transport (Q), which shortens the length of the downwind drift and the required setback distance.

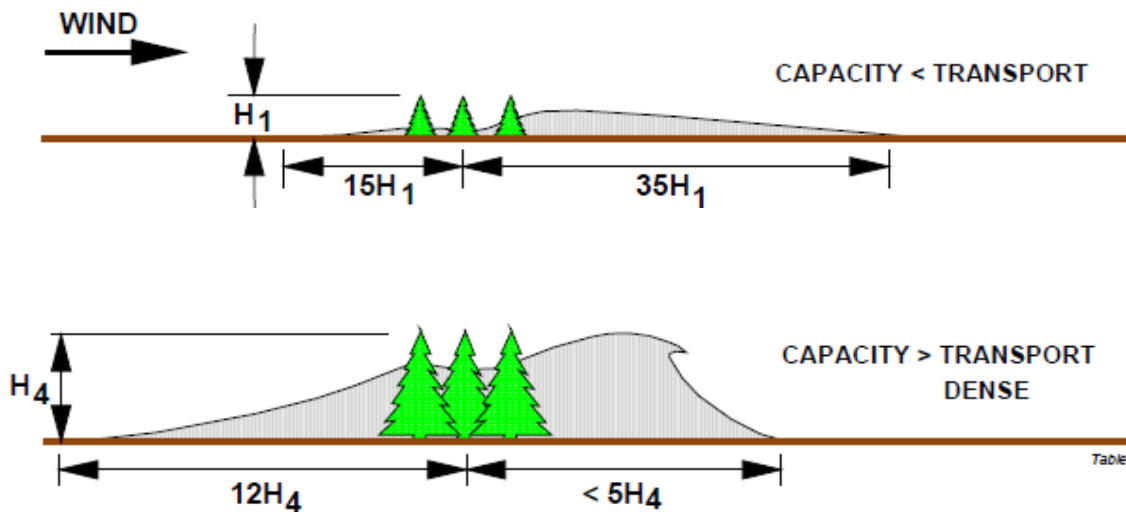


Figure 1: Changes in snowdrift shape and length as a result of changes in fence height, optical porosity, and capacity (Q_c) relative to snow transport (Q) of living snow fences (Tabler 2003, reproduced with permission)

Despite these remarks regarding reduced drift length as a result of capacity/transport ratio, Tabler (2003) provides a simplified model of predicted setback for living snow fences stating that, in light to moderate transport conditions, an adequate setback distance can be predicted from the model “... $(\sin \alpha)(35H_{req})$, where H_{req} is the required height of a structural fence at that location”. This model is similar to the standard setback approach for structural fences, with the key distinction that the coefficient of 35 is applied to the *required* fence height, not actual height. This model of predicted setback (D_{35}) may be adequate in some design scenarios *instead of more complex analysis*, but is not the most comprehensive model of setback for living snow fences offered by Tabler (2003), because it does not account for reduced drift lengths resulting from capacity/transport ratios that exceed 1:1 ($Q_c > Q$).

Multiplying by a coefficient of 35 (slightly modified by wind angle α) to determine the setback of a living snow fence is similar to the standard setback approach for structural snow

fences, and the two methodologies are often confused or not clearly distinguished from one another in the literature on living snow fences. An important nuance of the predicted setback model (**D₃₅**) is the use of *required* fence height, not mature height of vegetation, which may greatly exceed the former. However, this nuance is often omitted from reproductions of Tabler's work. The model of predicted setback does not address the possibility that mature living snow fences can store the majority or *entirety* of seasonal snow transport on the upwind side of the fence or in close proximity downwind, as a result of low porosity values and capacity/transport ratios much greater than 1:1 (**Q_c>>Q**).

These considerations are important because the drift length of living snow fences can be substantially influenced by capacity/transport ratio, as dictated by the aerodynamics governing snow deposition around porous barriers (i.e. snow fences). Under these aerodynamic principles, drift formation occurs in distinct stages around living snow fences as the drift growth progresses over the course of a snow season (Figure 2). Depending on the capacity of a snow fence relative to the quantity of snow transport (**Q_c/Q**), fences may or may not reach an equilibrium stage of full capacity over the course of a drift accumulation season. If a fence *does* reach equilibrium, wind and snow flows smoothly over the fence and drift, and no additional snow can be stored. Prior to reaching equilibrium however, there are several progressive stages of drift formation in which the upwind or downwind drift reaches a shifting point, which causes snow deposition to alternate between the upwind and downwind side of the fence.

The length of the downwind drift at any point during the accumulation season depends on the stage of drift formation the fence is in, which is dictated by the capacity/transport ratio of the

fence. This concept is illustrated in Figure 2 from Tabler (2003) showing the stages of drift formation around a scale model of a 50% porous structural snow fence (the same general principles of aerodynamics and drift formation apply to full scale living snow fences). This diagram is based on observed snow depths over a seven day period and shows how drift formation progresses in distinct stages, alternating from the upwind side to the downwind side of the fence, as dictated by turbulence patterns around the fence that shift continually as the drift grows.

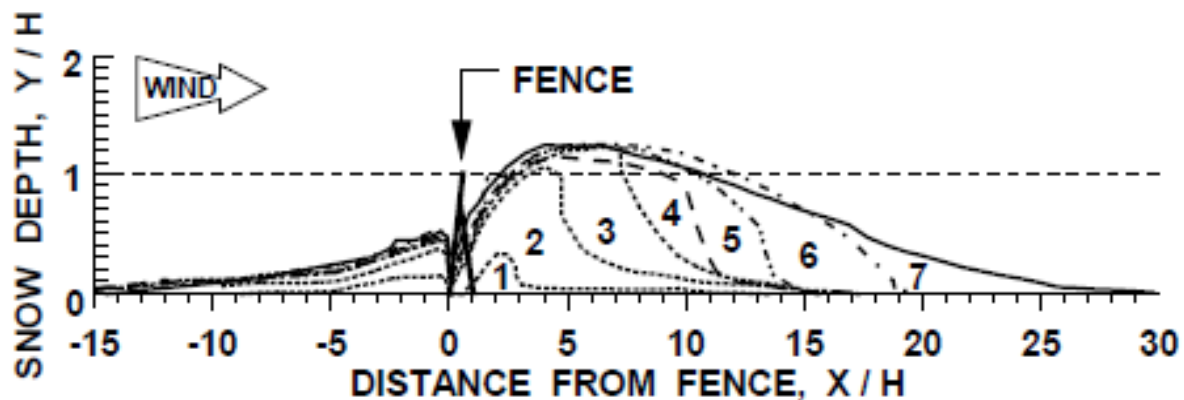


Figure 2: Progressive stages of snow drift formation around a 50% porous barrier (Tabler 2003, reproduced with permission)

The length of the downwind drift increases with the progressive stages of drift formation that are numbered one through seven in Figure 2. In stage one, the fence is only filled to a fraction of full capacity ($Q_c \gg Q$), and the length of the downwind drift is therefore only $10H$ (ten times the height of the fence), with the vast majority of the snow being stored within $3H$ downwind. In each successive stage of drift formation, snow is first deposited on the *upwind* side of the fence by a wind eddy. The stage one upwind drift forms first, followed by the stage one *downwind* drift. When the stage one downwind drift reaches a certain quantity of deposition, wind again

flows smoothly over the drift, snow deposition shifts back to the *upwind* side of the fence, and so on. When the capacity/transport ratio of a fence is greater than 1:1 ($Q_c > Q$), the *maximum* drift length over the course of the drift accumulation season is limited to one of the stages of drift formation that occurs prior to full capacity, and drift length is reduced to some fraction of the maximum $35H$. Higher capacity/transport ratios will limit seasonal drift accumulation to the earlier the stages of drift formation. The earlier the stage of drift formation, the shorter the downwind drift length will be. If the capacity/transport ratio of a fence substantially exceeds 1:1 ($Q_c \gg Q$), such as 20:1 or 100:1, the drift may never exceed the first stage of formation, and drift length will be reduced to a fraction of the maximum of length $35H$.

The progression of drift formation also varies depending on the optical porosity of the fence. Fences with porosity over 50% tend to create longer downwind drifts, whereas fences with less than 50% porosity tend to produce *shorter* downwind drift lengths, storing a higher percentage of snow on the upwind side of the fence (Tabler 2003). Tabler (2003) emphasizes the influence of porosity in conjunction with the stages of drift formation in regards to the drift length of living snow fences stating:

“...dense plantings of trees and shrubs act as solid barriers... there is little snow deposition on the downwind side of a solid fence until the upwind drift approaches equilibrium. If the storage capacity in the upwind drift is sufficient to store all of the design transport, then no significant drift will form on the downwind side of the barrier.”

Thus the length of the downwind drift and the required setback of living snow fences are dependent upon the height and porosity of the fence, and the capacity/transport ratio (Q_c/Q). Dense living snow fences (low porosity) with large capacity/transport ratios ($Q_c \gg Q$) have the potential to store the majority or *entirety* of seasonal snow transport (based on maximum snow

trapping efficiency of 90%) on the upwind side of the fence, or in close proximity downwind of the fence. Living snow fences can also have greater widths than structural fences due to multiple rows and horizontal growth of vegetation over time, which may further decrease the optical porosity of fences and cause snow to be trapped within the interior of the fence, further reducing the length of the downwind drift.

To calculate a drift length for living snow fences based on height, porosity, and incoming snow transport relative to storage capacity, Tabler (2003) combines two models of drift length developed for structural snow fences:

$$\mathbf{L/H} = 12 + 49\mathbf{P} + 7\mathbf{P}^2 - 37\mathbf{P}^3$$

Equation 1

...which estimates the length of an equilibrium (full capacity) drift that would form on a fence of a given porosity (**P**). And the model:

$$\mathbf{L/H} = 10.5 + 6.6(\mathbf{A/A_e}) + 17.2(\mathbf{A/A_e})^2$$

Equation 2

...which estimates the pre-equilibrium drift length that would occur on a fence when capacity exceeds transport. The variables **A/A_e** in Equation 2 represent the ratio of the (cross-sectional) area of the pre-equilibrium drift (**A**), to the (cross-sectional) area of the equilibrium drift (**A_e**). Notice that the output of these two models is in terms of **L/H**, or the length of the drift in terms of fence height. Tabler (2003) combines these two equations into one model of drift length for living snow fences:

$$\mathbf{L/H} = ([10.5 + 6.6(\mathbf{A/A_e}) + 17.2(\mathbf{A/A_e})^2]/34.3)(12 + 49\mathbf{P} + 7\mathbf{P}^2 - 37\mathbf{P}^3)$$

Equation 3

Tabler (2003) indicates that A/A_e is equivalent to the ratio of transport to capacity (Q/Q_c) of a living snow fence at the given height and porosity, but provides few additional details regarding the appropriate application of this model and does not explicitly state whether “H” in Equation 3 refers to the actual height (H) of the fence, or the required height (H_{req}). Despite this lack of information, Equation 3 is the most comprehensive model for estimating drift length and selecting an appropriate setback distance for living snow fences because it accounts for the key variable of capacity/transport ratio which drives drift length when capacity exceeds transport. However, this model has not been cited in any other literature on living snow fences, nor been tested with observed height and porosity values collected from living snow fences in the field.

Outside of Tabler (2003), the literature on selecting appropriate setback distances for living snow fences is limited and guidelines for modeling precise setback values are even sparser. Some literature is found in peer reviewed journals, but much is found in non-peer reviewed sources such as fact sheets from agricultural or forestry agencies, design manuals from transportation agencies, or university extension outreach publications. However, these are important sources of information that transportation staff and resource managers turn to for guidance when designing living snow fences. Most setback design guidelines in this literature provide only vague and conflicting information reproduced out of context from Tabler (2003) or other publications by Tabler. These sources generally do not report relevant research results, nor do they provide sufficient information to make informed setback decisions for living snow fences.

USDA (2011) contains a section on living snow fence design stating “...*typical setbacks range from 100-600 feet depending on site and geographic locations*”. Colorado State University Extension (2013) states “*trees should not be planted closer than 200 feet from the centerline of the road to provide adequate snow storage off the road*”. The Arbor Day Foundation (unknown date) states that fences should be planted at a minimum distance of “*200 feet in open country with snowy winters ...100 feet in areas with natural obstructions with less snowy winters*”. The New York State Department of Transportation (2012) states “*Living snow fences planted a distance ranging from 100 to 200 feet (based on available space) from the highway can greatly reduce blowing snow*”. The South Dakota Department of Agriculture (2004) states that living snow fences “*...should be located no closer than 175 feet from the centerline of the road*”. Barkley (unknown date) states “*Snow barriers should be placed at least 100’ away from driveways and roads*”. Cornell Cooperative Extension (2011) states “*Allow plenty of room for the leeward drift by locating the windward row of your windbreak 200 to 300 feet from the center of the road*”. Bratton (2006) states “*In flat open terrain, the windward row should be 150 to 250 feet from the center of the road*”. Streed and Walton (2001) state “*Snow fence density and height (H) control snow deposition distance*”. Shaw (1988) states “*Location of the living snow fence in relation to distance from the road is critical in that the deposition of snow must terminate short of the roadway*”. None of these 10 sources provide a model or any precise guidelines for calculating or selecting an appropriate setback distance for living snow fences. These recommendations are perceived not as useful design guidelines, but as precautionary remarks to avoid any recommendations that might result in snow fences being installed too close a roadway.

A limited number of sources go slightly beyond these vague and conservative estimates of setback and provide a small amount of additional details and methodology. Josiah and Majeski (2002) state *“Barrier density and height are most important in determining the placement of the living snow fence in relation to the road or area being protected. The barrier should be placed as close to the road or protected area as possible, but far enough away so that the downwind drift edge does not reach the area to be protected”*. This source also provides several diagrams from Tabler (1997), but does not provide instructions for adjusting the setback of living snow fences to account for changes in height, porosity, and capacity/transport ratio over time. Gullickson et al. (1999), in a 140 page design manual entitled *“Catching the Snow with Living Snow Fences”*, provide Equation 1 as above for calculating the length of the downwind drift and acknowledge that this equation produces a drift length output for fences that are filled to capacity. They go on to state *“The quantity of snow transport may never exceed the required fence height, meaning that taller trees can be placed closer to the road than $37H$ ”*, but do not provide further instructions on how to make this important adjustment. Shulski and Seeley (2001) also provide Equation 1 for calculating drift length, but again do not mention any adjustments for changes in height, porosity, and capacity/transport ratio as plants grow. Blanken (2009) states *“To avoid any snow deposition on the road, the minimum distance between the fence and the road for a fence with a porosity of 50% is $35H_{req}$ ”*. In summary, these sources recommend setback distances anywhere from 30 m to 180 m or more, and provide little information for calculating more precise values.

Of all the design recommendations for the setback of living snow fences offered by the aforementioned sources, Blanken (2009) is the perhaps the most useful because it provides a

clear methodology for calculating a precise setback value. Blanken (2009) also avoids a common misnomer by indicating that setback for living snow fences should be calculated based on *required* fence height (H_{req}), not the actual or mature height of the vegetation. However, this source does not address the complexity of setback for living snow fences, making no mention of the changes in height and porosity over time, nor the influence capacity/transport ratio on drift length. Thus it is clear from this literature review that the guidelines and models for estimating drift length and selecting an appropriate setback distances for living snow developed by Tabler (2003) have not been well understood, further researched, nor incorporated into the literature and design standards of living snow fences. This lack of complete, clear, and consistent guidelines has likely led to a similar hodgepodge of setback choices for living snow fences in the field. The current study therefore revisited and extrapolated the theoretical foundation of living snow fence structure and function established by Tabler (2003); collected data from newly planted and mature living snow fences of various ages, species, and planting patterns in New York State; and applied this data to the models of living snow fence function by Tabler (2000 and 2003).

3 METHODS AND MODELS

3.1 Selection of a Stratified Sample of Living Snow Fences

To undertake this project, it was necessary to first identify and select a subset of the statewide living snow fence population that could be further investigated within the constraints of time, resources, available information, and site accessibility. A stratified sample of living snow fences was selected using the available information and a combination of remote sensing and field investigations. The experimental unit of this study on which measurements were taken was one living snow fence, and the total number of fences investigated was 18. The primary source of information used was a list of living snow fences provided by the New York State Department of Transportation (2011). The NYSDOT list of living snow fences (Table 9, Appendix 3) contained the following categories of information for each fence listed, with some gaps in the information in each category: NYSDOT region, county, town, highway number, direction (i.e. east bound), reference (mile) marker start, reference marker end, species or vegetation type (i.e. “pine trees”), year installed, and fence length in miles.

Several vegetation types commonly used in living snow fences were investigated in this study. The two primary vegetation types that comprised 16 of the 18 fences were shrub-willow fences and conifer fences. The other two vegetation types were a standing corn fence and a honeysuckle shrub fence. The shrub-willow fences investigated in this study were planted prior to the start of this project through cooperative efforts between NYSDOT and SUNY-ESF. Accurate locations, survival rates, and the ease of site accessibility of these fences were therefore known to researchers at SUNY-ESF and the author prior to the start of this project. Some of these shrub-willow fences were also found to be included in the NYSDOT (2011) list of living

snow fences. Shrub-willow fences were selected by the author based on the ease of accessibility, and to represent a broad range of ages and cultivars. A majority of shrub-willow fences investigated in this study are planted along a 10 km stretch of interstate highway I-81, and county route 287 which runs parallel to I-81, between Tully and Preble, NY. These fences are a minimum of 250 meters apart from one another; and vary in age, cultivar, and soil classification; and were therefore assumed to be unique sampling units independent of one another. The other shrub-willow living snow fences investigated in this study were planted through cooperative efforts of SUNY-ESF and NYSDOT in various years, using various cultivars, in various locations across New York State.

The corn, honeysuckle, and conifer fences investigated in this study were identified from the NYSDOT (2011) list of fences, and through conversations with regional NYSDOT officials. These fences were planted in various years and in various locations across the state by NYSDOT. The exact location, survival rates, and accessibility of these fences were not known to the author prior to the start of this project, and were therefore identified in the landscape from the basic information provided by NYSDOT list of living snow fences (2011), and by using a combination of remote sensing and site inspection based on the criteria below:

Based on remote sensing:

- Fence is within 650 km roundtrip driving distance of Syracuse, NY.
- Fence is clearly distinguishable, at or near the designated reference marker, using the geographic information software (GIS) ESRI ArcMap 10.0 or in aerial photos from the Google Earth 6.1.0 software.
- Fence survival is confirmed with a local NYSDOT official prior to site visit if possible.

Based on site inspection:

- Fence can be located in the landscape at or near the confirmed reference marker or nearest cross street.
- Site and fence can be safely accessed for sampling.

- Fence has a survival rate of approximately 75% or greater upon initial visual inspection.
- Fence has at least one continuous section 50 m in length to sample (if there is more than one section 50 m in length, the most easily accessible section will be sampled).

Species Identification and Vegetation Type

The NYSDOT list of living snow fences (2011) contained general information about the vegetation type of each fence, but often lacked precise information. Species and cultivars were therefore identified as accurately as possible for the 18 fences investigated in this study.

Cultivars of shrub-willow fences were accessed and identified from records and plot maps retrieved from the data archive of the Willow Project at SUNY-ESF. For fences other than shrub-willow, species were preliminarily identified from the NYSDOT (2011) list, and plant samples from each fence were collected in the field to confirm or clarify the documented species. Photos of bark, stems, leaves (needles), and general plant form were taken at each fence; and physical samples of stems, leaves, and fruit (where possible) were collected and later verified as specific species and cultivars as accurately as possible using a combination of online and print resources (Brand MH 2013, Hardin et al. 2001, USDA 2013). All species were assigned a “vegetation type” classification in one of four categories: shrub-willow, conifer, corn, or honeysuckle. While honeysuckle is not a category of “vegetation type” per se, it is a type of shrub that appears to be planted for living snow fences more often than others shrub species (NYSDOT 2011, Shulski and Seeley 2001), and is therefore categorized as one of the four “vegetation types” in this study. Photos from various distances and angles were taken at each fence, and one or two photos from each fence were included in Appendix 2.

Fence Age (years since planting)

The measure of time in this study is referred to as fence “age” and indicates the number of years since the fence was planted. Age was calculated by subtracting the documented year of fence installation from the current year 2013. In other words, fence “age” is a measure of the number of years since the fence was planted, *not* the actual number of years since the vegetation was first propagated which varied and was unknown in some cases. Age is therefore a measure of the age of the *fence*, not the vegetation itself. All measurements on vegetation were taken in the late fall of 2012 and winter 2012/2013 after leaf-fall when plants were dormant (or primarily dormant in the case of conifers). This was after the primary summer growing season had passed, so age reflects the number of growing seasons since planting, and the function of the fence in the following winter. For example, an “age 3” fence represents the data observations collected in the winter following the third growing season after planting.

This classification system was used to normalize the reported ages of different fences planted with rooted and unrooted planting stock. For shrub-willow fences, fence age does represent true age, since this vegetation type it is planted as unrooted stem cuttings. Shrub-willow fences are generally coppiced after the first growing season, so the reported age of shrub-willow fences is the age of the root systems and the stool, with the age of the stems generally being one less than the reported age. For conifer and honeysuckle fences planted by NYSDOT, the number of years since the planting stock (potted or balled trees) was first propagated was unknown and not investigated as part of this study. It was generally assumed however, that the age of the planting stock at the time of fence planting was approximately three to six years, based on observations of the height of young conifer fences and the author’s knowledge nursery practices and NYSDOT living snow fence and roadside tree planting practices.

3.2 Remote Measurements

Fence Length

Fence length was measured remotely on each fence using the ruler tool in Google Earth. Length was measured linearly from end to end, starting at the beginning of the fence vegetation, continuing to the end of the fence vegetation (Figure 3). If multiple sections of fence existed at a site, but were not directly connected to the fence section being sampled (i.e. there was an intentional gap between sections), the additional sections were *not* included in the measurement of fence length reported in this study.

Sampling Plots

Due to large and variable fence lengths, a sampling plot 100 m in length was established at each fence to simplify and standardize the sampling process, and a series of measurements for each variable was taken within the 100 m sampling plot (Figure 3, Figure 4). The final height, porosity, row spacing, plant spacing, fetch, and setback values of each fence reported in the results of this study represent the mean of a series of four or eight measurements (depending on the variable), taken within the 100 m sampling plot at each fence. Sampling plots were initially established remotely by measuring fence length in Google Earth, calculating the approximate linear center of the fence, and measuring the 100 m sampling plot around the linear center point (Figure 3).

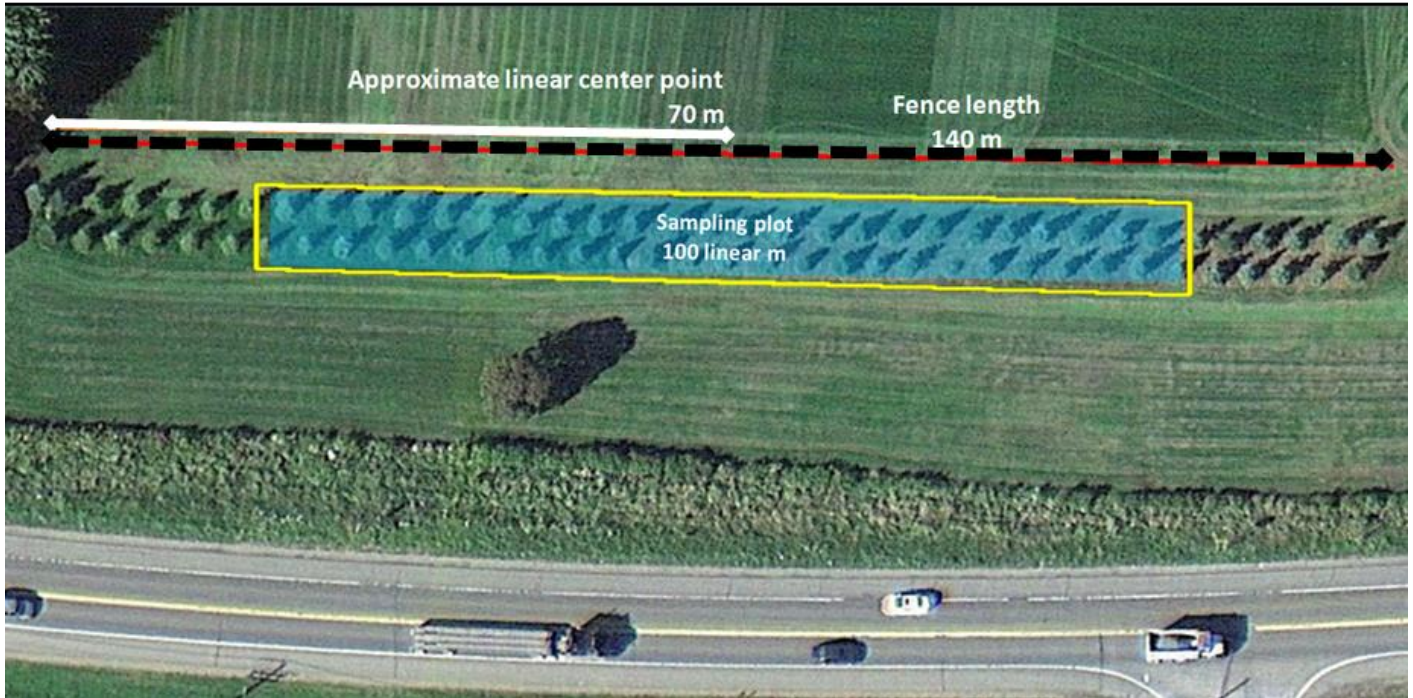


Figure 3: Diagram of fence length and 100 m sampling plot used in this study, established around the approximate linear center of living snow fence Pomfret-conifer-5

Setback and fetch distances were measured remotely within the 100 m sampling plot using Google Earth (Figure 4). Field plots based on remote measurements were established on the ground using aerial photo prints, a metric tape measure, flagging tape, and pacing to approximate certain distances. Height, porosity, row spacing, and plant spacing were measured in the field. Seventeen of the 18 fences investigated were a minimum of 115 m in length, creating a buffer of at least 7.5 m on either side of the 100 m sampling plot to avoid potential edge effects. For the one exception in which the fence length was less than 100 m (Columbia-conifer-3), the sampling plot was set equal to the entire fence length, less 7.5 m on either side, and measurements were taken at approximately equidistant spacing within the reduced plot.

Observed Setback Distance (D)

The observed setback distance (**D**) in meters at each fence was measured remotely using the ruler tool in Google Earth, starting at the widthwise center of the fence vegetation, continuing at a perpendicular angle to the nearest visible edge of roadway pavement. Four measurements at equidistant spacing were taken across the length on the 100 m sampling plot at approximately 1 m, 33 m, 66 m, and 99 m (Figure 4), and the four measurements were averaged giving the reported setback (**D**) value for each fence.

Fetch Distance (F)

Fetch distance (**F**) at each fence was measured remotely using Google Earth. Fetch was measured at four approximately equidistant points within the 100 m sampling plot at approximately 33 m spacing (Figure 4). Fetch was measured from the widthwise center of the fence vegetation at a perpendicular angle, to the first obstacle upwind that was *assumed* to alter wind patterns and cause snow deposition, such as any building, group of trees, forest, etc. The mean of the four fetch measurements was calculated, giving the reported fetch value of each fence. The fences investigated in this study were generally bordered on the upwind side by large agricultural fields, so open space relative to obstructions was clearly distinguishable in aerial photos for most sites. Divisions between multiple fields in the fetch area existed at a few sites, but field divisions generally appeared to be sparse in vegetation so they were not considered obstacles, even though sparse vegetation and agricultural fences may cause some amount snow trapping.

Roads were also *not* considered an obstacle that would create drifting in this study, despite the fact that roadside ditches, guard rails, and snow banks created by snow plows have the potential to disrupt wind patterns and cause drifting (Tabler 2003). In this regard, the reported fetch values are potentially high estimates of the total area contributing to the blowing snow problem at each site. However, fetch distances were only measured at perpendicular angles relative to the fence, because the “attack angle” of the wind was assumed to be 90° for all fences and a more precise wind angle was not investigated as part of this study. At some sites, the reported fetch distance would have been larger had it been measured at angles other than 90° from the fence, potentially contributing to higher fetch and snow transport values. The former and latter considerations regarding fetch distance were assumed to approximately balance each other out, and provide the best possible estimate of fetch under the given constraints, and sufficiently accurate estimates of average seasonal snow transport (**Q**) across all fences investigated in this study.

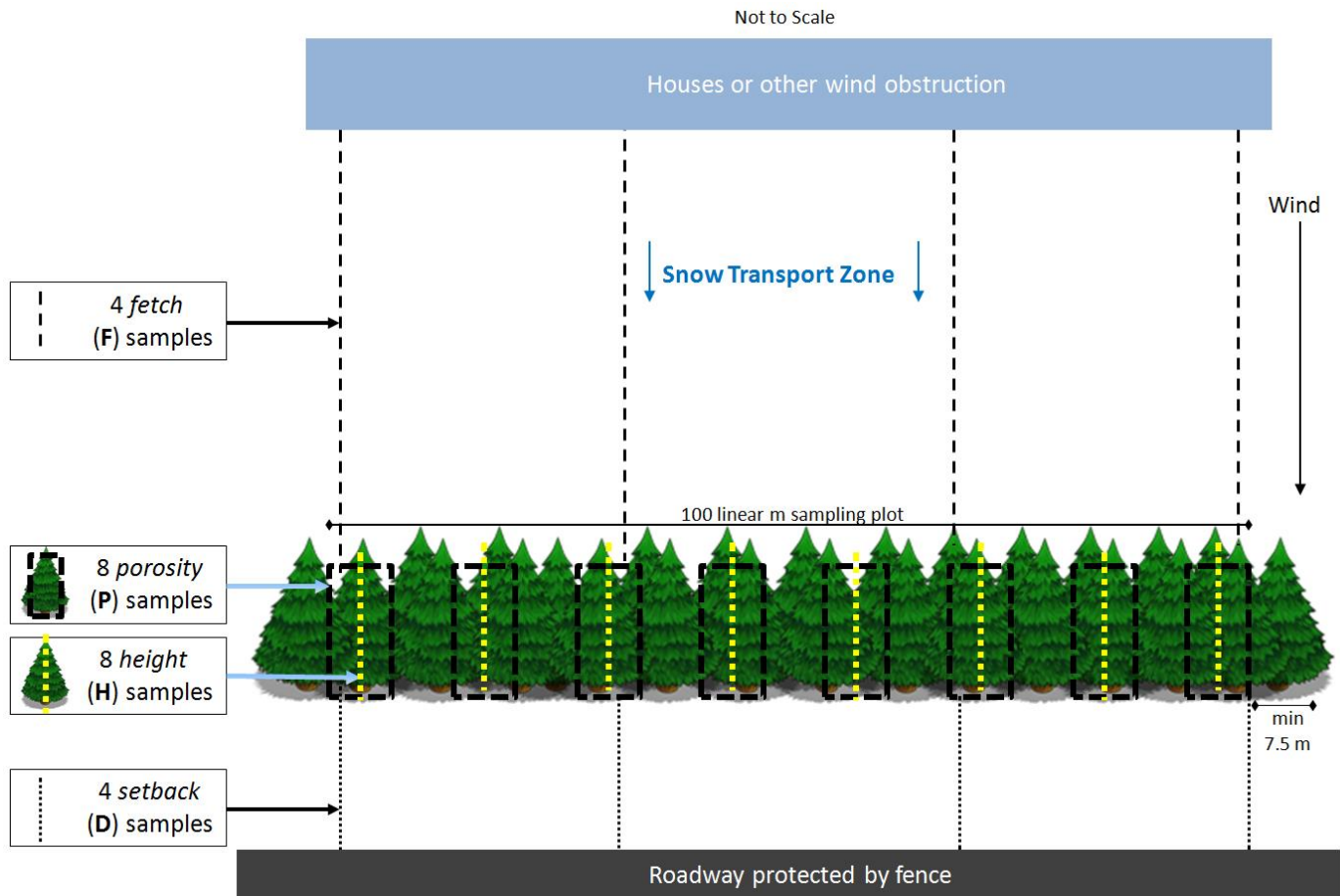


Figure 4: Sampling diagram of remote measurements of site fetch and setback; and field measurements of fence height and optical porosity

3.3 Field Measurements

Height (H)

Height of living snow fences was measured using a telescoping height pole. Eight measurements were taken within the 100 m sampling plot on the downwind side of each fence. Measurements were taken at roughly equidistant spacing of 12.5 m as determined by pacing the sampling plot (Figure 4). The pole was extended to the maximum height of the vegetation, at which the height was recorded. The mean of the eight measurements was calculated giving the

reported height value (**H**) of each fence. Height was measured to the nearest centimeter in the field and reported values were rounded to the nearest decimeter for clarity.

Porosity (P)

Two techniques of sampling optical porosity were used in this study; a chroma-key backdrop technique used on shrub-willows, honeysuckle, and corn fences; and a high contrast photography technique used on conifer fences. All fences were photographed in late fall or early winter 2012/2013 after deciduous species had completely defoliated, using a Nikon AW100 16 megapixel point and shoot camera. Shrub-willow, corn, and honeysuckle fences were photographed using a chroma-key backdrop technique previously developed by researchers at SUNY-ESF, and refined for this study. For each measurement of optical porosity, the fence was photographed with a 1 m wide by 3 m tall red back drop held directly behind the fence (Figure 5). The backdrop was custom designed for this study and ordered from a theatrical fabric supply company. The backdrop was made from the synthetic fabric “*Weblon*”, which was selected for characteristics relevant to chroma-key photography such as color, opaqueness, and texture. The intended use also dictated that the fabric have characteristics suited for field work in remote locations and outdoor conditions such as durability, waterproofing, wrinkle-free, and ease of cleaning. The fabric was selected to be red in color to create a strong color contrast between the backdrop and the fence vegetation.



Figure 5: Picture taken of living snow fence Tully-B-willow-6 with a red chroma-key backdrop held behind the fence to create a strong color contrast and accurately sample optical porosity

Pole pockets 5 cm in diameter were custom sewn into either side of the backdrop and a pair of 3 m aluminum poles was inserted into the pockets to frame the backdrop. Each photograph was taken by the author at a perpendicular angle to the fence, at a distance of approximately 2.5 m upwind or downwind, with a research assistant holding the backdrop as close to the vegetation as possible at a perpendicular angle to the ground. Eight photographs were taken within the 100 m sampling plot of each fence at approximately equidistant spacing of 12.5 m (Figure 4), at approximately the same points where height measurements were taken.

This chroma-key backdrop technique, initially developed for shrub-willow snow fences, also worked for the honeysuckle fence and corn fence, but was not found to be a viable technique for

conifer fences due to differences in fence height, porosity, and width, between the different vegetation types. Specifically, conifer fences were found to have generally lower porosity values (higher density of vegetation) and larger widths, making the edges of the chroma-key backdrop difficult to distinguish. This led to difficulties in framing the photos in the field, and processing the photos with Adobe Photoshop CS4 11.0. The photographic methods of Loeffler et al. (1992) were therefore to create high contrast photographs of conifer fences investigated in this study.

To create as much contrast between the vegetation and open space as possible, photos of conifer fences were taken from the windward or leeward side of the fence, with the sun on the opposite side of the fence when possible to increase the light infiltration through the open space in the fence. The contrast setting on the camera was slightly increased in the field, and the image contrast was also increased slightly in Adobe Photoshop. This technique produced a photographic sample that was functionally equivalent to photos produced by the chroma-key technique, in which a distinct color contrast was created between the photographed plant parts and the open space (porosity) of the fence (Figure 6). As with the chroma-key technique, photographs were taken at a perpendicular angle to the fence at a distance of approximately 2.5 m, in order to photograph an area of the fence approximately 1 m in width by 3 m in height. Eight photographs were taken on each fence at approximately 12.5 m spacing across the sampling plot (Figure 4).



Figure 6: Examples of processed photos used to measure optical porosity from the chroma-key technique (left, Tully-B-willow-6) used for shrub-willow, honeysuckle, and corn fences; and high contrast technique (right, Cobleskill-conifer-11) used for conifer fences

The chroma-key and high contrast photographs were digitally processed to determine the optical porosity value using Adobe Photoshop. Photos were cropped to include only the area in front of the red backdrop, or the approximate 1 m x 3 m sampling area in conifer photos. The approximate 1 m x 3 m sampling area for conifer fences was determined by cropping out approximately 10% of the total pixels in the photo around the top and sides, as was done to crop the backdrop on the chroma-key photos, creating a 1 width by 3 height image containing approximately the same number of pixels as the cropped chroma-key photos (Figure 6). The open space (porosity) in each photo was selected using the wand selection tool in Adobe Photoshop, and the selection was cleared to a white background to verify that all open space was selected and no plant parts were selected. The pixel count of the selected open space was recorded using the histogram tool and divided into the total pixel count of the cropped image, giving the percentage of open area (porosity). The mean porosity of the eight processed photos was calculated giving the reported porosity value (**P**) for each fence.

Plant and Row Spacing

Plant spacing was measured by holding a metric tape at the center of the base of one plant, extending the tape 10 m linearly down the fence, and counting the number of plant bases that fell entirely or partially within the 10 m length of tape. This process was repeated four times within the 100 m sampling plot of each fence, at approximately equidistant spacing. The number of plants in the four 10 m plots was averaged and divided by 10, giving the plant spacing in meters reported for each fence. Row spacing was measured by extending the tape from the center of the base of one plant, widthwise across the snow fence, until it was equal with the center of the base of the nearest plant in the next row, and the number of meters was recorded. For fences with

more than two rows, the tape was extended to the base of the nearest plant in the last row, and the number of meters was divided by the number of rows. This process was repeated four times within the 100 sampling plot of each fence at approximately equidistant spacing, and the four measurements were averaged giving the reported row spacing in meters for each fence.

3.4 Models of Snow Trapping Function

Average Annual Snow Transport (Q)

Snow transport (**Q**) was calculated for each snow fence site in this study using the following model from Tabler's (2000) report "*Climatologic Analysis for Snow Mitigation in New York State*":

$$Q = 1500(0.17)(S_{we,AS})(1-0.14^{F/3000})$$

Equation 4

Where:

Q is average annual snow transport quantity in units of t/m

(0.17) is the assumed snow relocation coefficient (**C_r**)

(**S_{we,AS}**) is the water equivalent of snowfall over the drift accumulation season in meters

F is the fetch distance in meters

The assumed **C_r** value of 0.17 represents a statewide average provided and described by Tabler (2000) as the recommended value for designing snow fences in New York State when a more precise value is not known or measured for the site in question. A more precise value for this variable was not investigated as part of this study and the fences investigated are in various locations across the state (Figure 7), so this was assumed to be a sufficiently accurate assumption

for the purposes of this study. Snowfall water equivalent over the drift accumulation season ($S_{we,AS}$) in the above model was estimated using the following model from Tabler (2000):

$$S_{we,AS} = (-695.4 + 0.076 * \mathbf{Elev} + 17.108 * \mathbf{Lat})(0.10)$$

Equation 5

Where:

$S_{we,AS}$ is water equivalent of snowfall over the drift accumulation season in inches

\mathbf{Elev} is the elevation of the snow fence site in meters

\mathbf{Lat} is the degrees north latitude of the snow fence site

(0.10) is the assumed water equivalent of snowfall in NY State (Tabler 2000)

The output of this model was converted from inches into meters for this study. Note that “snowfall over the drift accumulation season” is different than the total annual snowfall for a location, the former being delimited by snowfall that does not contribute to the sustained growth of the snow drift around the fence (i.e. snow that falls and melts before the drift achieves sustained growth, or snow that falls after the drift has started to permanently melt in the spring). Elevation and latitude values were measured at the linear center of each fence in Google Earth. The 0.10 value for the water equivalent of snowfall was assumed to be an accurate statewide assumption based on Tabler (2000), and a more precise value at each site was not investigated as part of this study.

Snow Storage Capacity (Q_c)

Snow storage capacity (Q_c) for each snow fence in this study was calculated using the observed height and porosity values from each fence and the following model from Tabler (2003):

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

Equation 6

Where:

Q_c is the snow storage capacity of the fence in units of t/m

P is the observed optical porosity value of the fence

H is observed height of the fence in meters

Capacity/Transport Ratio

The capacity/transport ratio indicates the ratio of snow storage capacity of a fence (Q_c) to the average annual snow transport quantity (Q), both in units of t/m, creating a unitless ratio of fence capacity relative to site transport (X:1).

$$\text{capacity/transport ratio} = Q_c/Q$$

Equation 7

Required Height (H_{req})

The required height (H_{req}) of each snow fence, based on the average annual transport (Q) at the fence site, was estimated using the following model from Tabler (2003):

$$H_{req} = (Q/8.5)^{0.455}$$

Equation 8

Where:

H_{req} is the required height of the fence in meters

Q is the average annual transport in t/m

Predicted Setback (D_{35})

The predicted setback (D_{35}) was calculated for each fence in this study using the following model from Tabler (2003):

$$D_{35} = (\sin\alpha)35H_{\text{req}}$$

Equation 9

Where:

D_{35} is the predicted setback distance in meters

α is the degree of the angle of prevailing winter wind relative to the roadway

H_{req} is the required height of a 50% porous fence in meters

The angle of the wind to road α was assumed to be 90° in all cases for this study because all fences were oriented parallel with the roadway, which is the design standard when wind angle is between 55° and 90° (Tabler 2003), and a more precise wind direction was not investigated as part of this study.

Models of Drift Length

Two models of drift length in units of meters were investigated in this study, based on two possible interpretations of the drift model for living snow fences (Equation 3) from Tabler (2003):

$$L/H = ([10.5 + 6.6(A/A_e) + 17.2(A/A_e)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)$$

Equation 3

Equation 3 produces output values in terms of L/H , or drift length in terms of fence height.

When applying actual data collected from living snow fences to Equation 3 (as done in this study), it is pragmatic to multiply the L/H output of Equation 3 by a height value in units of

meters to obtain a final value of drift length (**L**) that is also in units of *meters*. Drift lengths in units of meters are more practical and meaningful than abstract terms of **L/H** when evaluating the function and setback possibilities of living snow fences and the interpreting results and implications for living snow fence design.

The two possible interpretations of Equation 3, and the two subsequent drift models investigated in this study, differ in terms of multiplying the **L/H** output of Equation 3 by either the *observed* fence height (**H**) (model 1), *or*, multiplying the **L/H** output of Equation 3 by the *required* fence height (**H_{req}**) (model 2). Tabler (2003) does not explicitly state which of these two possibilities is the correct methodology for converting the **L/H** output of Equation 3 into a meaningful drift length value in *meters*. This nuance is an important distinction for the design of living snow fences that substantially impacts the output of drift length values, and is in need of further clarification and analysis. Both possible interpretations and conversions of Equation 3 were therefore analyzed in this study as drift model 1, and drift model 2, as extrapolated below.

Drift Model 1

The length of the downwind drift (**L**) in meters produced by drift model 1 was calculated for each fence investigated in this study using the following model adapted from Tabler 2003:

$$L = ([10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)(H)$$

Equation 10

Where:

L is the length of the downwind drift in meters

Q is the estimated average annual snow transport at the fence in t/m

Q_c is the estimated fence capacity in t/m

P is the observed fence porosity

H is the observed fence height in meters

Note that (Q/Q_c) is substituted here for (A/A_e) from the original notation of Equation 3, which Tabler (2003) describes as equivalent and substitutable ratios. The variable (**A**) refers the (cross-sectional) area of the drift that would form around a fence of the required height (**H_{req}**), at the observed quantity of snow transport (**Q**). The variable (**A_e**) refers to the (cross-sectional) area of the *equilibrium* drift that would form around the fence at the observed capacity (**Q_c**), if transport were great enough to fill the fence to equilibrium (full capacity). If transport is *not* great enough to fill the fence to equilibrium, the drift area and drift length will be some fraction of the maximum. Thus the ratio of transport to capacity (Q/Q_c) is approximately equivalent to the ratio of drift area (**A**), to the area of the equilibrium drift (**A_e**) (Tabler 2003). This ratio (the inverse of capacity/transport ratio used in this study) is the critical driver of this model that modifies the length of the downwind drift based on fence capacity relative to seasonal snow transport, according to the stages of drift formation described by Tabler (2003) and reexamined in section 2.3 of the current study.

This ratio is therefore expected to modify the drift length output of model 1 and model 2 so that the greater the capacity/transport ratio, the shorter the downwind drift output becomes. In other words, in models of drift length driven by capacity/transport ratio, there should be a significant negative relationship between the variables of capacity/transport ratio and drift length, with drift length decreasing as capacity/transport ratio increases. Applying data from a chronosequence of living snow fences should provide a series of outputs for model 1 and model

2 that can validate or invalidate the expected response of drift length in both models, to the predictor variable of capacity/transport ratio.

Drift Length Model 2

The length of the downwind drift (**L**) produced by drift model 2 was calculated for each fence investigated in this study using the following model adapted from Tabler 2003:

$$L = ([10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)(H_{req})$$

Equation 11

Where:

L is the length of the downwind drift in meters

Q is the estimated average annual snow transport at the fence in t/m

Q_c is the estimated fence capacity in t/m

P is the observed fence porosity

H_{req} is the required height of the fence based on the transport quantity (**Q**)

The variables (**Q/Q_c**) are again substituted here for (**A/A_e**) as above.

Statistics

Bar charts, means, medians, and standard deviations were produced in Microsoft Excel. Statistical analysis was performed using the Minitab 16 Statistical Software program. Fence age (years since planting) was the predictor variable for the response variables of fence height, optical porosity, and snow storage capacity. Simple linear regressions were performed to test the null hypothesis that the slope of the regressions was equal to zero. The null hypothesis was rejected and regressions were reported as significant when the p value was less than or equal to 0.05 ($p \leq 0.005$). Scatter plots, r^2 values, and fitted equations for the regression models were

produced in Minitab. Regressions for each response variable were performed amongst all fences, and also grouped by vegetation type. It was expected that, amongst all fences, there would be a strong positive relationship between age and height, a strong negative relationship between age and porosity, and a strong positive relationship between age and capacity. In addition to linear regressions, non-linear regressions were performed for the predictor variable of capacity/transport ratio versus the response variables of downwind drift length in drift model 1, and downwind drift length in drift model 2. A list of all regressions performed and the corresponding r^2 values, p values, and S values were included in Table 5 at the end of the Results section.

Metric to English Conversion

The methods and models, results, and discussion of this study were performed and reported in SI metric units. However, NYSDOT and most US transportation agencies, to which this study will be most relevant, use English units of measurement. For this reason Table 2, Table 3, and Table 4 containing the all the values of results of this study were reproduced using English units in Appendix 1 as Table 6, Table 7, and Table 8.

4 RESULTS

4.1 Fence Location, Species, and Planting Pattern

The 18 living snow fences investigated in this study were located in six NYSDOT regions and 10 counties within New York State (Figure 7, Table 1). Each fence was assigned an identification tag using the name of the town the fence was located in, followed by the vegetation type, and the age (years since planting) of the fence (i.e. Spencerport-conifer-6). If more than one fence was investigated in the same town, a letter, starting with “A”, was added after the name of the town (i.e. Preble-A-willow-9). The highway number, side of the road the fence was planted on (i.e. south bound), and the approximate NYSDOT highway reference marker at which the fence begins were also included in Table 1. One or two photos taken at each fence were included in Appendix 2.

Seven shrub-willow cultivars, five conifer species, one honeysuckle cultivar, and one corn cultivar were sampled in this study (Table 2). Fence age (years since planting) ranged from 1 - 11 years, constituting an eleven year chronosequence. The mean age was 5.7 ± 3.0 years. Fence length ranged from 67 - 482 m and the mean was $237 \text{ m} \pm 115 \text{ m}$. Eleven fences consisted of two rows; four fences consisted of a single row; two fences consisted of three rows; and the corn fence consisted of eight rows. Plant spacing and row spacing of shrub-willow fences was 0.61 m and 0.76 m respectively. The one exception was Grand-Gorge-willow-7, which consisted of a single row of shrub-willow at 0.31 m plant spacing. Amongst the six conifer fences, plant spacing ranged from 1.83 – 3.66 m. For conifer fences with multiple rows, three fences had 3.05 m row spacing and one fence had 2.13 m row spacing.

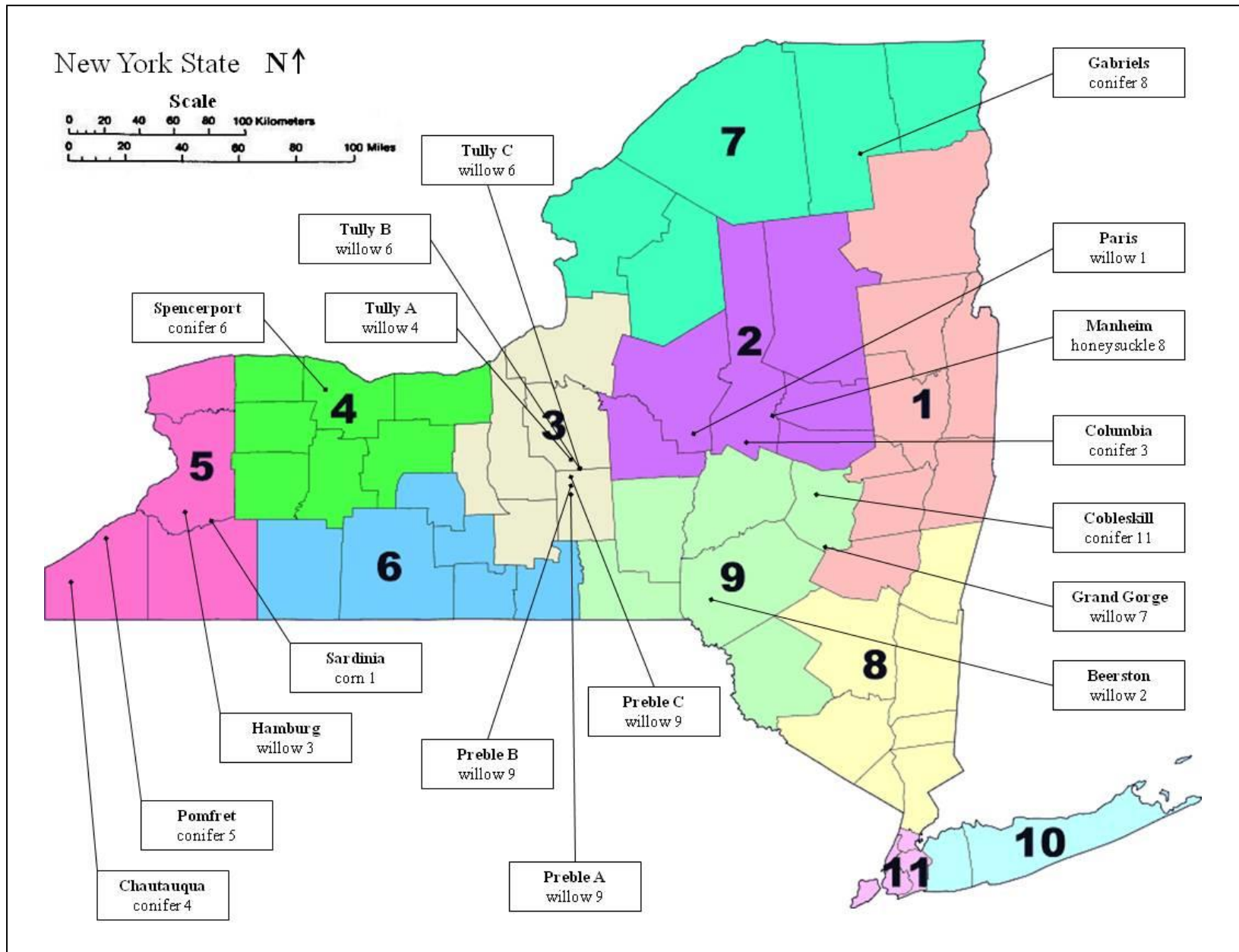


Figure 7: Map of New York State showing NYSDOT regions, approximate locations, and identification tags (town name, vegetation type, age) of the 18 living snow fences investigated in this study

Table 1: Fence identification tags and location data of 18 living snow fences investigated in this study, sorted by NYSDOT region and county

NYSDOT Region	County	Fence Identification Tag (Town - vegetation type - age)	Highway Number	Highway Side	NYSDOT Reference Marker Start
2	Herkimer	Columbia - conifer - 3	28	SB	28 2304 1067
2	Herkimer	Manheim - honeysuckle - 8	167	SB	167 2302 3024
2	Oneida	Paris - willow - 1	12	SB	12 260 41119
3	Cortland	Preble A - willow - 9	I-81	SB	81I 3202 3090
3	Cortland	Preble B - willow - 9	I-81	SB	81I 3202 3086
3	Cortland	Preble C - willow - 9	I-81	SB	81I 3202 3084
3	Onondaga	Tully A - willow - 4	I-81	SB	81I 3303 1020
3	Onondaga	Tully B - willow - 6	281	SB	281 3302 1011
3	Onondaga	Tully C - willow - 6	281	SB	281 3302 1011
4	Monroe	Spencerport - conifer - 6	531	WB	531 430 12017
5	Chautauqua	Chautauqua - conifer - 4	394	EB	17 5201 1055
5	Chautauqua	Pomfret - conifer - 5	60	SB	60 5201 3244
5	Erie	Hamburg - willow - 3	219	SB	219 531 21112
5	Erie	Sardinia - corn - 1	16	SB	16 5302 1009
7	Franklin	Gabriels - conifer - 8	86	SB	86 7201 1047
9	Delaware	Beerston - willow - 2	10	EB	10 930 11218
9	Delaware	Grand Gorge - willow - 7	30	SB	30 9502 1010
9	Schoharie	Cobleskill - conifer - 11	I-88	WB	88I 9507 1081

Table 2: Taxonomy and planting pattern of 18 living snow fences investigated in this study, sorted by vegetation type and age (years since planting)

Fence Identification Tag (Town - vegetation type - age)	Scientific Name	Common Name	Fence Length (m)	Plant Spacing (m)	Number of rows	Row Spacing (m)	Fetch Distance (m)
Sardinia - corn - 1	<i>Zea mays</i>	standing corn rows	350	0.10	8	0.75	340
Manheim - honeysuckle - 8	<i>Lonicera tatarica</i>	Arnold red honeysuckle	181	0.91	1	-	206
Paris - willow - 1	<i>Salix purpurea, Salix miyabeana</i>	var. SX64, Fishcreek	115	0.61	2	0.76	275
Beerston - willow - 2	<i>Salix miyabeana, Salix purpurea</i>	var. SX64, Fishcreek	410	0.61	2	0.76	128
Hamburg - willow - 3	<i>S. sachalinensis, S. dasyclados</i>	var. SX61, 98101-61	264	0.61	2	0.76	780
Tully A - willow - 4	<i>Salix miyabeana, Salix purpurea</i>	var. SX64, Fishcreek	482	0.61	2	0.76	750
Tully B - willow - 6	<i>Salix caprea hybrid</i>	var. S365	235	0.61	2	0.76	185
Tully C - willow - 6	<i>S. sachalinensis x S. miyabeana</i>	var. Sherburne	235	0.61	2	0.76	185
Grand Gorge - willow - 7	<i>Salix purpurea</i>	shrub-willow purpurea	158	0.31	1	-	171
Preble A - willow - 9	<i>S. miyabeana, S. sachalinensis</i>	var. SX64, SX61, 98101-61, 9870-42	192	0.61	2	0.76	480
Preble B - willow - 9	<i>S. miyabeana, S. sachalinensis</i>	var. SX64, SX61, 98101-61, 9870-42	115	0.61	2	0.76	370
Preble C - willow - 9	<i>S. miyabeana, S. sachalinensis</i>	var. SX64, SX61, 98101-61, 9870-42	116	0.61	2	0.76	538
Columbia - conifer - 3	<i>Picea abies</i>	Norway spruce	67	3.05	3	2.13	855
Chautauqua - conifer - 4	<i>Picea pungens</i>	blue spruce	185	3.66	3	3.05	620
Pomfret - conifer - 5	<i>Picea pungens</i>	blue spruce	140	3.66	2	3.05	437
Spencerport - conifer - 6	<i>Pseudotsuga menziesii</i>	Douglas-fir	373	1.83	1	-	157
Gabriels - conifer - 8	<i>Thuja occidentalis</i>	northern white cedar	345	2.13	1	-	470
Cobleskill - conifer - 11	<i>Abies concolour</i>	white fir	302	3.05	2	3.05	318
Mean 5.7	-	-	237	1.3	2	1.3	404
Median 6.0	-	-	235	0.6	2	0.8	370
Standard Deviation 3.0	-	-	117	1.2	1.6	1.0	230

4.2 Height and Porosity

There was a significant positive linear relationship ($p < 0.001$) between age and height (**H**) amongst all fences investigated in this study (Figure 8) as expected. The height of Sardinia-corn-1 was the lowest of any fence including a shrub-willow fence of the same age (Paris-willow-1) (Table 3). Manheim-honeysuckle-8 fell approximately 2 m below the height trend amongst all fences. Conifer fences were fairly evenly distributed above and below the trend. Shrub-willow fences were concentrated above or slightly below the trend. Preble-C-willow-9 had the largest observed height of any fence. Cobleskill-conifer-11 was slightly shorter than Spencerport-conifer-6, Grand-Gorge-willow-7, Preble-A-willow-9, and Preble-B-willow-9. In general, willow fences had a slightly faster height growth rate (Height = $8.644 + 0.5753 \text{ Age}$, $r^2 = 0.852$, $p < 0.001$) than the trend amongst all fences. Height of conifer fences generally increased with age, but there was no significant relationship between age and height amongst conifer fences ($p = 0.149$).

When the observed height of fences (**H**) was compared to predicted values of required fence height [Equation 8: $\mathbf{H}_{\text{req}} = (\mathbf{Q}/8.5)^{0.455}$] at 50% porosity, the observed height was greater than the required height for every fence investigated in this study (Figure 9, Table 3). The mean required height was $1.0 \text{ m} \pm 0.3 \text{ m}$, whereas the mean observed height was $3.8 \text{ m} \pm 1.7 \text{ m}$. Paris-willow-1 had 0.5 m of excess height beyond the required amount, and Beerston-willow-2 had 1.3 m of excess height. Columbia-conifer-3 had 1.6 m of excess height. For all fences ages five and older, the observed height was approximately two to six times greater than the required height (Figure 9). Sardinia-corn-1 had 0.4 m of excess height. Manheim-honeysuckle-8 had 1.4 m in excess height despite being well below the trend of height growth amongst all fences.

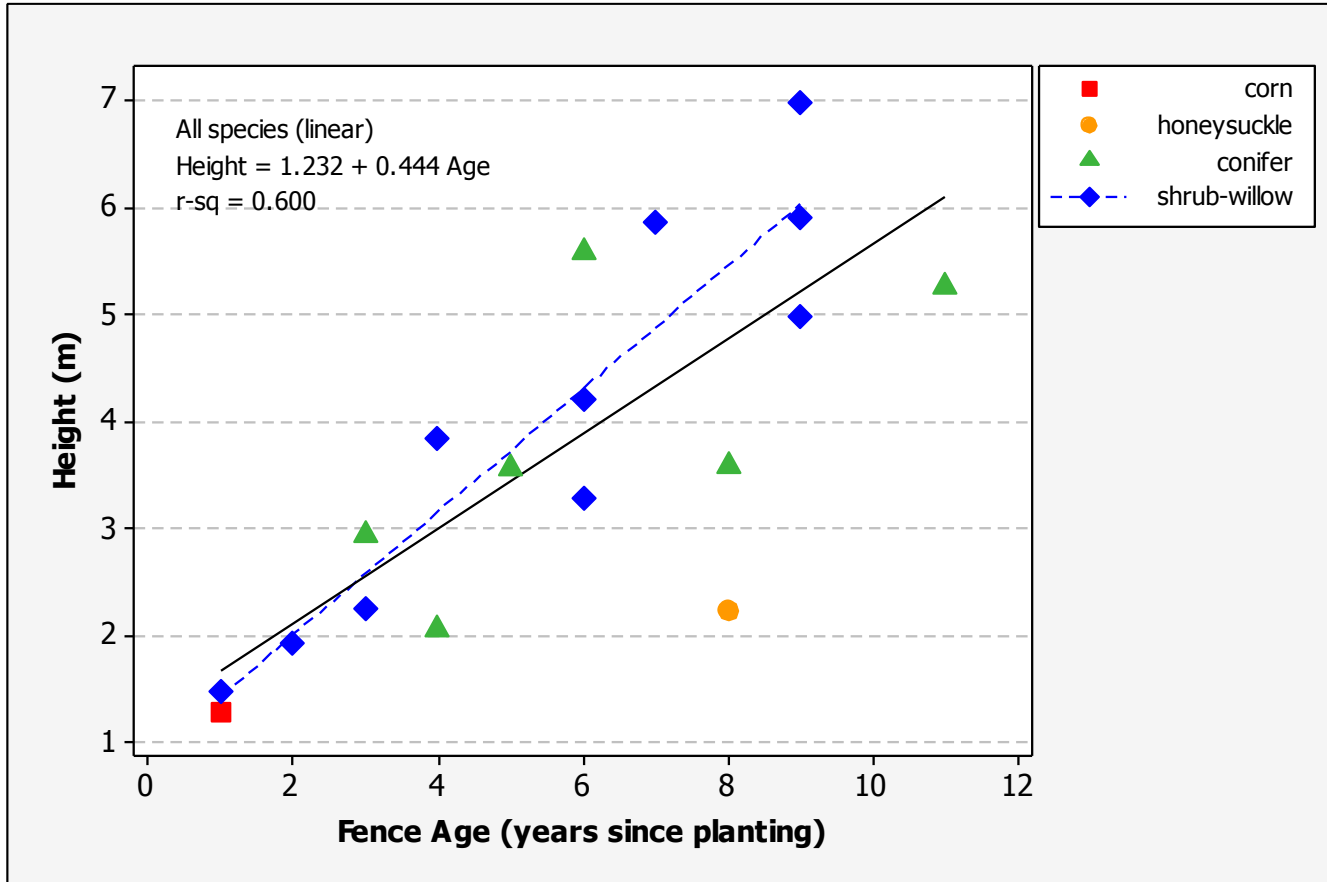


Figure 8: Age (years since planting) versus height (**H**) of 18 living snow fences of various species in New York State, grouped by vegetation type

Table 3: Summary of results for variables related to snow trapping function of 18 living snow fences of various species in New York State, sorted by vegetation type and age (years since planting)

	H_{req}	H	P	Q_c[*]	Q[*]	Q_c/Q[*]
Fence Identification Tag (Town - Vegetation Type - Age)	Required Height (m)	Observed Height (m)	Porosity	Capacity (t/m)	Transport (t/m)	Capacity/Transport Ratio
Sardinia - corn - 1	0.9	1.3	0%	5	7	<1
Manheim - honeysuckle - 8	0.8	2.2	63%	47	5	10
Paris - willow - 1	1.0	1.5	92%	<1	8	<1
Beerston - willow - 2	0.6	1.9	88%	<1	3	<1
Hamburg - willow - 3	1.5	2.3	77%	29	19	1.5
Tully A - willow - 4	1.2	3.9	52%	167	13	13
Tully B - willow - 6	0.7	3.3	61%	113	4	30
Tully C - willow - 6	0.7	4.2	62%	192	4	50
Grand Gorge - willow - 7	0.7	5.9	47%	411	4	110
Preble A - willow - 9	0.9	5.0	33%	239	7	34
Preble B - willow - 9	1.0	5.9	39%	387	9	44
Preble C - willow - 9	1.1	7.0	26%	430	10	43
Columbia - conifer - 3	1.3	2.9	27%	66	15	4
Chautauqua - conifer - 4	1.2	2.1	61%	40	12	3
Pomfret - conifer - 5	0.9	3.6	41%	130	7	19
Spencerport - conifer - 6	0.7	5.6	29%	280	3	82
Gabriels - conifer - 8	1.4	3.6	39%	128	17	8
Cobleskill - conifer - 11	1.0	5.3	38%	297	8	39
Mean	<i>1.0</i>	<i>3.8</i>	<i>50%</i>	<i>185</i>	<i>9</i>	<i>27</i>
Median	<i>1.0</i>	<i>3.6</i>	<i>50%</i>	<i>167</i>	<i>8</i>	<i>16</i>
Standard Deviation	<i>0.3</i>	<i>1.7</i>	<i>20%</i>	<i>141</i>	<i>5</i>	<i>31</i>

Note* - The **Q_c** and **Q** values reported in this table were rounded to the nearest t/m for clarity. The capacity/transport ratios (**Q_c/Q**) reported in this table are the rounded ratio of the *actual* capacity and transport values modeled in this study

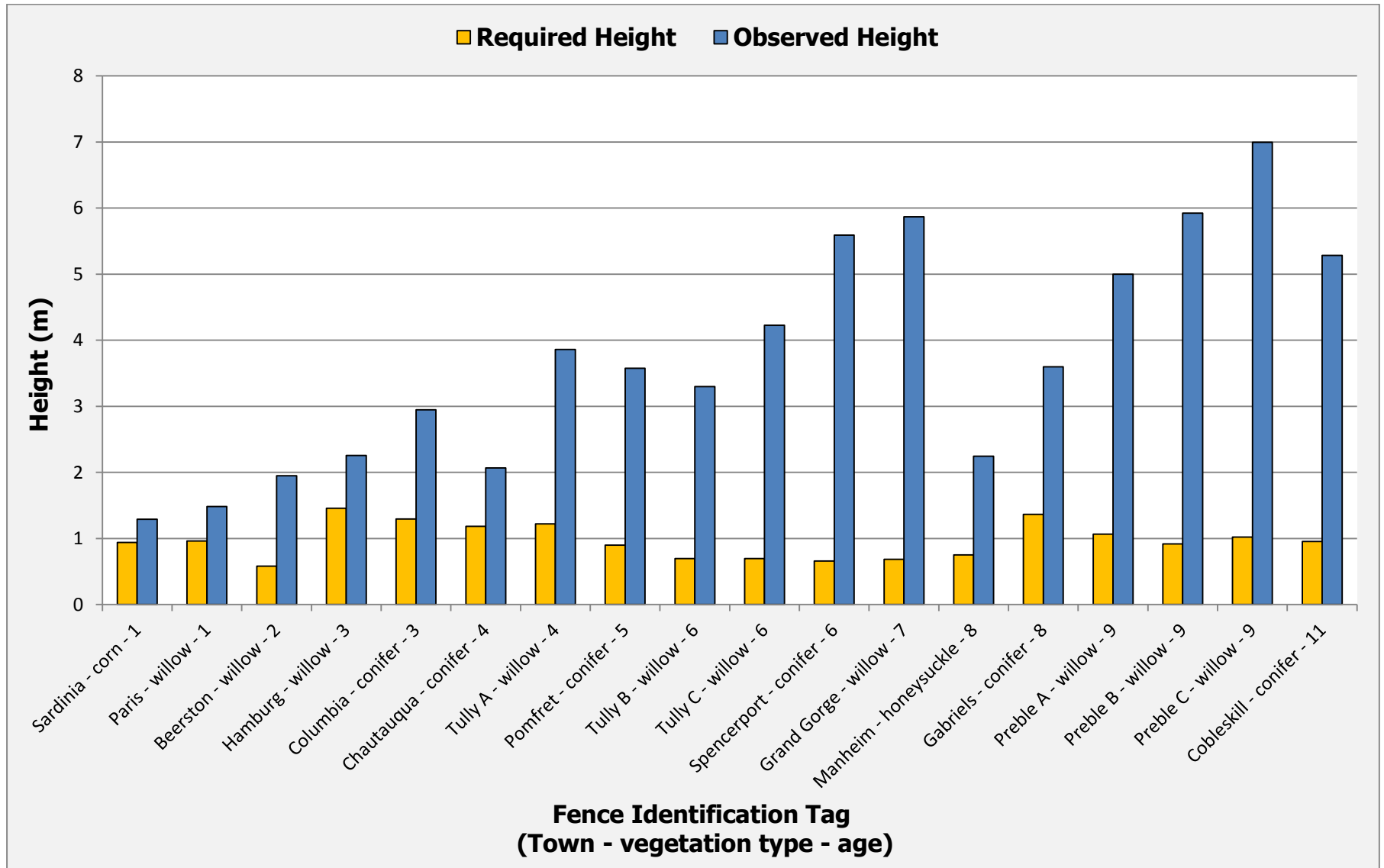


Figure 9: Observed height (**H**) compared to the predicted required height (**H_{req}**) of 18 living snow fences of various species and ages (years since planting) in New York State

There was a significant negative relationship ($p = 0.005$) between age and porosity (**P**) across 17 fences in this study (Figure 10). This was the expected result based on the fact that vegetation generally fills in open space (porosity) over time as plants grow. Sardinia-corn-1 was excluded from this regression due to the observed porosity value of 0% (non-porous) at age 1, which made it a distinct outlier from all other porosity values (Figure 10). This low porosity value was due to the small plant spacing, and eight-row planting pattern (five more rows than any other fence) (Table 2). Columbia-conifer-3 was substantially below the porosity trend amongst all fences, due to the small spacing, three-row configuration, and the large size of trees three years after planting (Figure 23). The other conifer fences were near or below the trend line. Shrub-willow fences were near or above the trend up to age 7. Of the three age 9 shrub-willow fences, one was near the trend line and two were below it.

Manheim-honeysuckle-8 fell substantially above the trend amongst all species due to the single-row configuration and 0.91 m plant spacing. By comparison, the three other single-row fences (one shrub-willow and two conifer fences) in this study were similar ages, but had had lower porosities than Manheim-honeysuckle-8 (Table 3). Compared to the trend amongst all fences, porosity of shrub-willow fences declined more rapidly and consistently (Porosity = $0.976 - 0.0712 \text{ Age}$, $r^2 = 0.892$, $p < 0.001$) (Figure 10). There was no significant relationship between age and porosity amongst conifer fences ($p = 0.877$) indicating that porosity for fences of this vegetation type changed very little between ages 3 and 11.

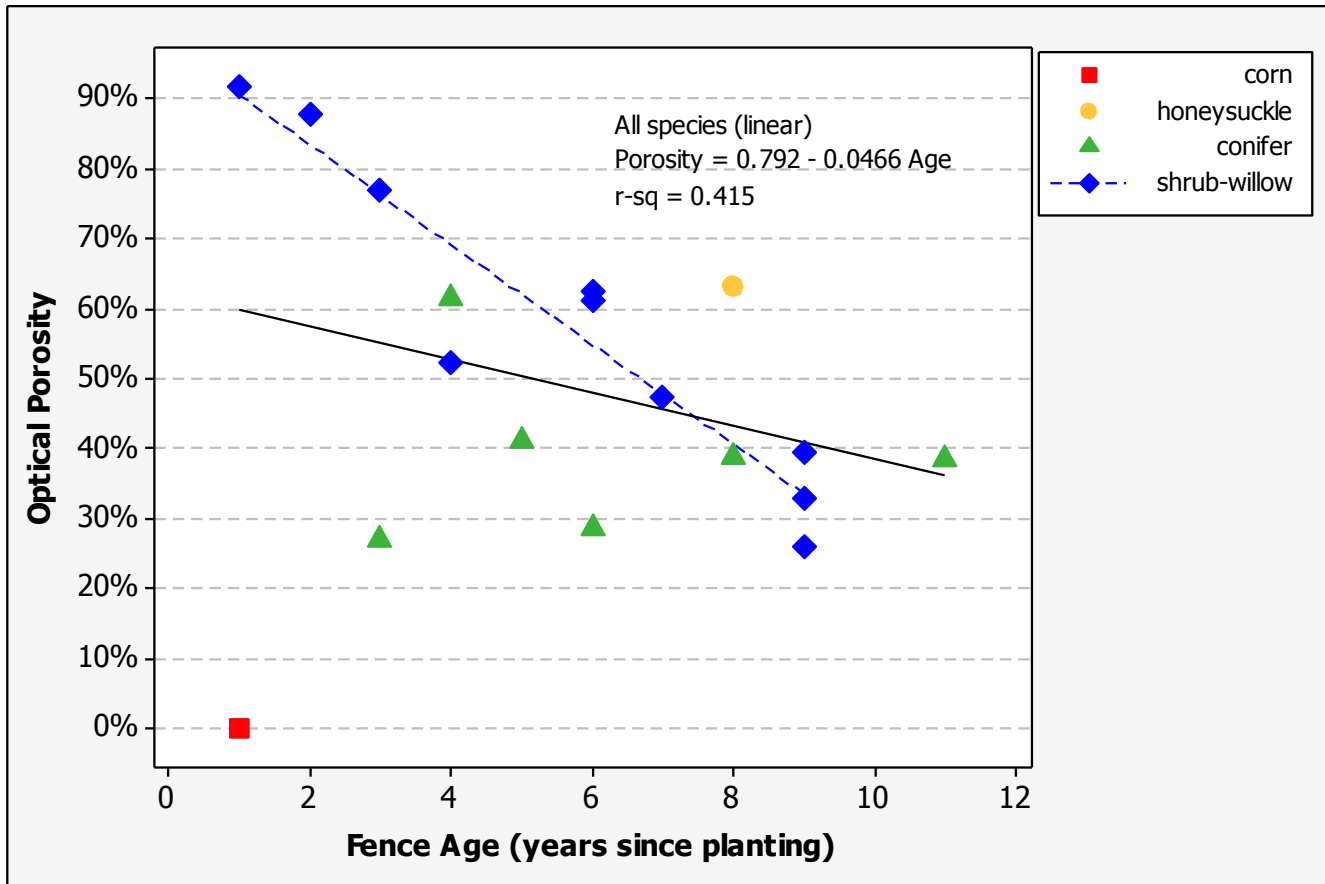


Figure 10: Age (years since planting) versus optical porosity (**P**) of 18 living snow fences of various species in New York State, grouped by vegetation type

4.3 Capacity and Transport

There was a strong positive linear relationship ($p < 0.001$) between age and capacity (Q_c) amongst all fences investigated in this study (Figure 11). The trend in capacity was similar to the trend in height (Figure 8) as expected, capacity being primarily driven by height and slightly modified by porosity [Equation 6: $Q_c = (3 + 4P + 44P^2 - 60P^3) H^{2.2}$]. Conifer fences were near or below the trend line of all fences, the one exception being Spencerport-conifer-6 which was ~100 t/m above the trend. Shrub-willow fences were near the trend line of all fences, with the exceptions of Grand-Gorge-willow-7, Preble-B-willow-9 and Preble-C-willow-9, all three of which had capacity over 350 t/m and were ~100 t/m above the trend. Manheim-honeysuckle-8

was ~150 t/m *below* the capacity trend of all fences, and had a capacity similar to age 3 conifer and shrub-willow fences. Capacity of shrub-willow fences increased over time at a slightly faster rate than the trend amongst all fences (Capacity = -77.9 + 49.0 Age, $r^2 = 0.769$, $p = 0.001$). Capacity of conifer fences increased at a slightly slower rate than the trend amongst all fences (Capacity = -12.2 + 27.5 Age, $r^2 = 0.554$, $p = 0.090$).

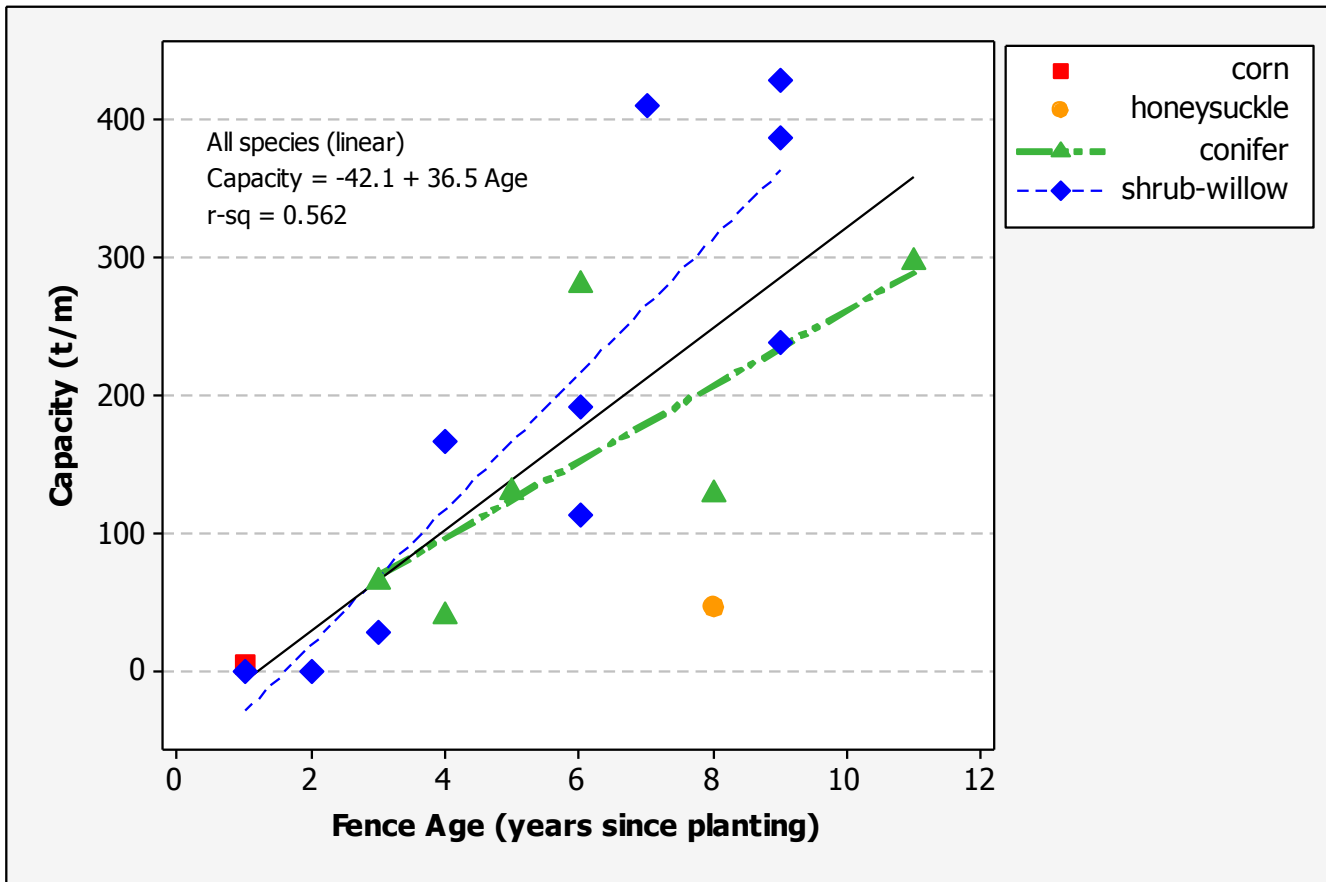


Figure 11: Age (years since planting) versus capacity (Q_c) of 18 living snow fences of various species in New York State, grouped by vegetation type

Snow transport (Q) across all sites ranged from 3 - 19 t/m, and the mean was 9 t/m \pm 5 t/m (Table 3, Figure 7). This range of seasonal snow transport values was classified as “very light”

(<10 t/m), or “light” (10 - 19 t/m), by Tabler (2003) in terms of the severity of blowing snow problem. Snow transport (**Q**) of Sardina-corn-1 was 7 t/m, which was greater than the fence capacity of 5 t/m. The height (**H**) of Sardinia-corn-1 exceeded the required fence height (**H_{req}**), but the *low* porosity value of 0% (non-porous) reduced the storage capacity. The capacities of age 1 and age 2 shrub-willow fences (Paris-willow-1 and Beerston-willow-2) were both below 1 t/m which was less than the snow transport at these sites. The height of these fences again exceeded the required fence height, but *high* porosity values of 92% and 88% negated any substantial storage capacity. All fences in this study age 3 and older had capacity values that exceeded transport (Table 3, Figure 12) indicating that fences were fully functional (**Q_c ≥ Q**) at early ages.

The capacity/transport ratio (**Q_c/Q**) of Hamburg-willow-3 was 1.5:1 (Figure 13), meaning that after three growing seasons, the storage capacity of this fence was 1.5 times the quantity of snow transport occurring at the site in average year. The **Q_c/Q** ratio of Columbia-conifer-3 was 4:1 after three growing seasons. The **Q_c/Q** ratio for Tully-A-willow-4 was 13:1, nearly 10 times the **Q_c/Q** ratio at Hamburg-willow-3, which was the same vegetation type and only one year younger. The second youngest conifer fence Chautauqua-conifer-4 had a **Q_c/Q** ratio of only 3:1, but the third youngest conifer fence (Pomfret-conifer-5) was 19:1. For all fences age five and older, the **Q_c/Q** ratio was between 8:1 and 110:1, indicating that fences had large amounts of excess storage capacity at early ages. The largest **Q_c/Q** ratios were observed at Grand-Gorge-willow-7 (110:1), and Spenerport-conifer-6 (82:1). All capacity/transport ratios were partly a result of the capacity of the fences, but also the transport values which were slightly different at each site. For example, Spenerport-conifer-6 was near the median age, had one of the *highest*

capacity values, but also equaled the *lowest* transport value which combined to give it the second highest Q_c/Q ratio amongst all fences. Overall, the fences investigated in this study had snow storage capacity greater than the site transport after three growing seasons, and continued to add excess storage capacity in a linear trend over the eight subsequent years of the chronosequence, further increasing the Q_c/Q ratio.

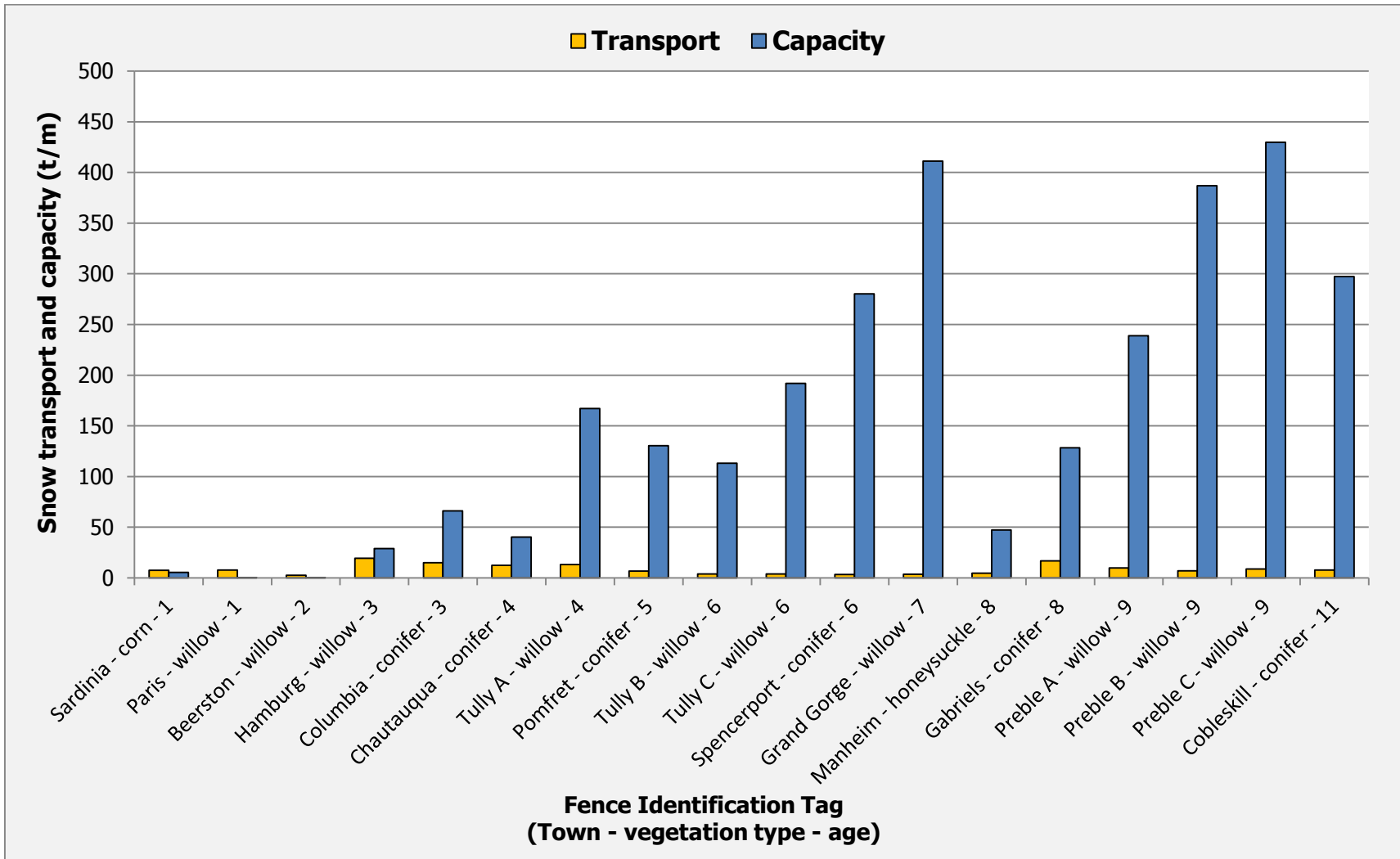


Figure 12: Fence capacity (Q_c) relative to the quantity of snow transport (Q) at each site for 18 living snow fences of various species and ages (years since planting) in New York State

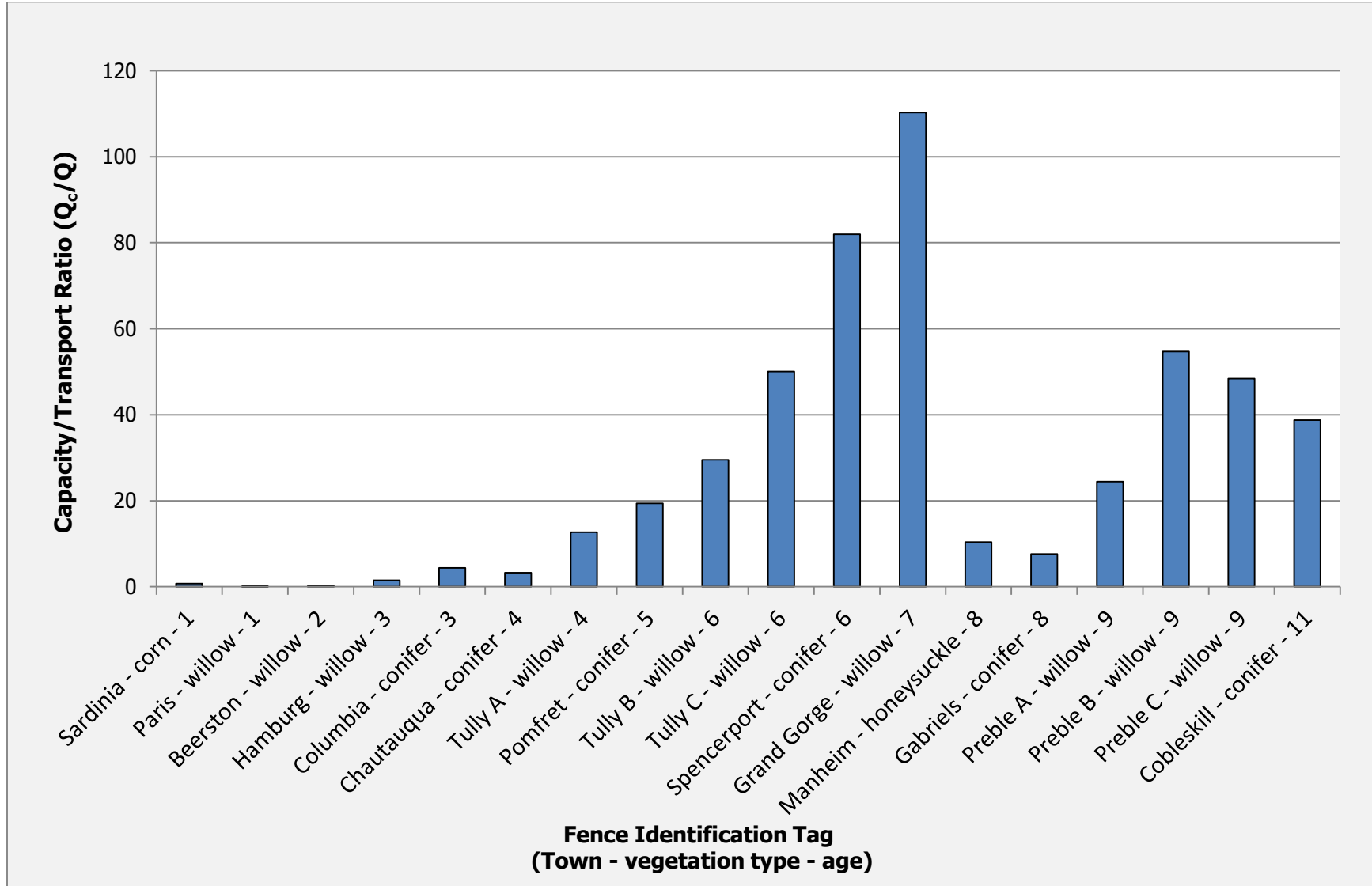


Figure 13: Capacity/Transport ratio (Q_c/Q) of 18 living snow fences of various species and ages (years since planting) in New York State

4.4 Setback and Drift Length

There was no significant relationship between observed setback distance (**D**) and the predictor variables of height (**H**), capacity (**Q_c**), snow transport (**Q**), capacity/transport ratio (**Q_c/Q**), nor predicted setback (**D₃₅**) ($p > 0.417$). This indicates that there is no standard methodology or model being consistently applied in the selection of setback distances for living snow fences in New York State. The choice of setback distances was likely influenced by site conditions and limitations, but likely also reflects the literature on living snow fences which provides no consensus nor precise guidelines on this topic. Observed setback (**D**) ranged from 9 m - 95 m. The range of *predicted* setback values (**D₃₅**) was considerably smaller at 18 m - 46 m. The mean of observed setback distances was 34 m \pm 24 m (Table 4). The mean of *predicted* setbacks was 30 m, which was only 4 m less than the observed mean. However, the standard deviation of predicted values was only \pm 8 t/m, compared to the larger standard deviation of observed values of \pm 24 t/m. Observed setback values thus showed a large maximum value, a large range, and a large standard deviation.

When the length of the downwind drift (**L**) was predicted for all fences using *drift model 1*, the mean drift length was 42 m \pm 12 m (Table 4). The range of predicted drift lengths produced by drift model 1 was 25 m - 68 m. The drift length values produced by drift model 1 were *larger* than the observed setback distance for 12 out of 18 fences in this study, and larger than the predicted setback (**D₃₅**) for 14 of 18 fences.

$$L = ([10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)(H)$$

Equation 10

Table 4: Observed setback, predicted setback, and drift model outputs of 18 living snow fences of various species in New York State, sorted by vegetation type and age (years since planting)

Fence ID Tag (Town - Vegetation Type - Age)	Observed Setback Distance (D) (m)	Predicted Setback Distance (D₃₅) (m)	Predicted Drift Length Model 1 (m)	Predicted Drift Length Model 2 (m)	Capacity/Transport Ratio (Q_c/Q)
Sardinia - corn - 1	71	29	25	18	<1
Manheim - honeysuckle - 8	38	24	25	8	10
Paris - willow - 1	26	30	52	34	<1
Beerston - willow - 2	27	18	68	20	<1
Hamburg - willow - 3	28	46	47	30	1.5
Tully A - willow - 4	42	38	41	13	13
Tully B - willow - 6	10	22	34	7	30
Tully C - willow - 6	10	22	44	7	50
Grand Gorge - willow - 7	95	22	57	7	110
Preble A - willow - 9	13	33	43	9	34
Preble B - willow - 9	10	29	54	8	44
Preble C - willow - 9	9	32	53	8	43
Columbia - conifer - 3	52	41	28	12	4
Chautauqua - conifer - 4	59	37	28	16	3
Pomfret - conifer - 5	31	28	34	9	19
Spencerport - conifer - 6	37	21	44	5	82
Gabriels - conifer - 8	17	43	36	14	8
Cobleskill - conifer - 11	41	30	48	9	39
Mean	<i>34</i>	<i>30</i>	<i>42</i>	<i>13</i>	<i>27</i>
Median	<i>31</i>	<i>30</i>	<i>43</i>	<i>9</i>	<i>16</i>
Standard Deviation	<i>24</i>	<i>8</i>	<i>12</i>	<i>8</i>	<i>31</i>

There was no significant relationship ($p = 0.136$) between capacity/transport ratio and the drift length outputs produced by drift model 1 (Figure 14). When the capacity/transport ratio of fences was between 0 and 15:1 in drift model 1, the drift length output ranged between 25 m and 68 m. When capacity/transport ratio was greater than 15:1 in drift model 1, drift length generally *increased* and ranged between 25 m and 57 m. This general increase in drift length was *not* consistent with the expected trend of decreasing drift length in response to increasing capacity/transport ratio in accordance with the stages of drift formation from Tabler (2003).

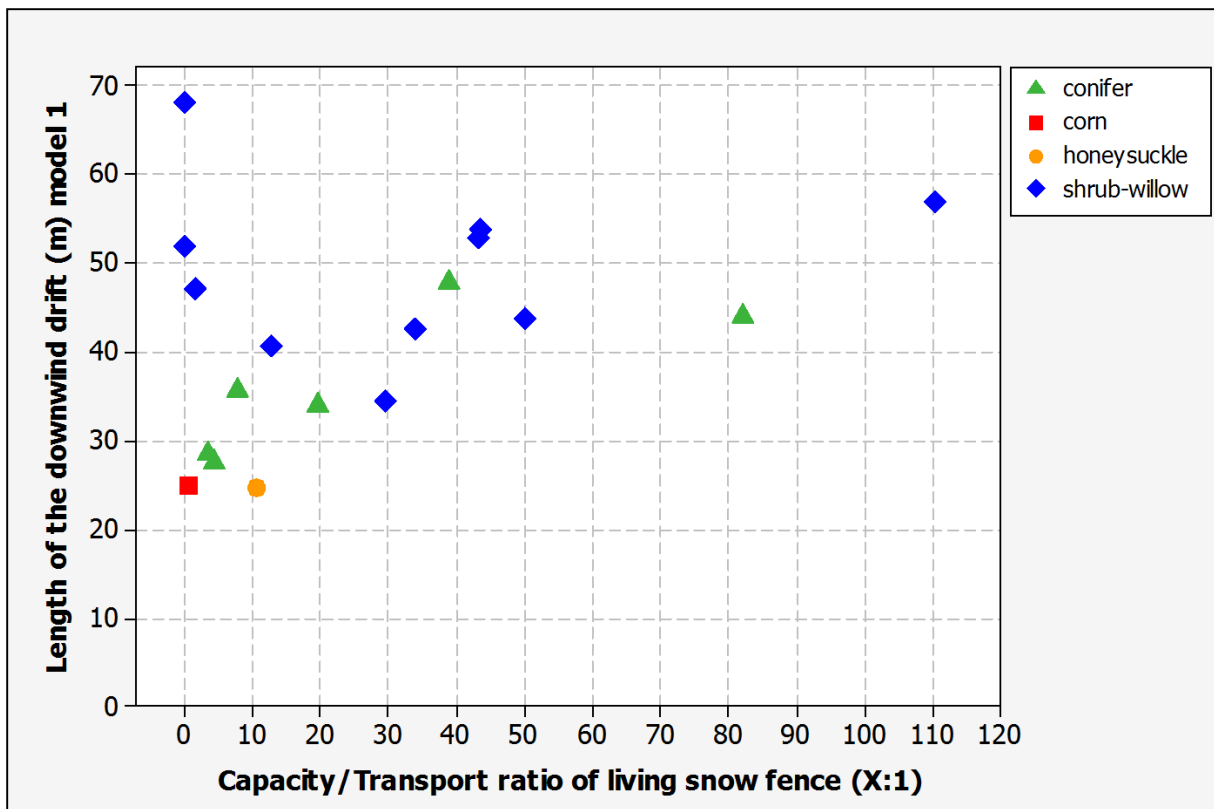


Figure 14: Capacity/Transport ratio versus length of the downwind snow drift as predicted by drift model 1 for 18 living snow fences of various ages (years since planting) and species in New York State

When drift length (**L**) was predicted for all fences using *drift model 2*, the mean drift length was 15 m ±8 m. The range of predicted drift lengths produced by model 2 was 5 m - 34 m. The drift length values produced by drift model 2 were *smaller* than the observed setback distance for 16 out of 18 fences in this study, and smaller than the predicted setback (**D₃₅**) for 16 of 18 fences (Table 4).

$$L = ([10.5 + 6.6(Q/Q_c) + 17.2(Q/Q_c)^2]/34.3)(12 + 49P + 7P^2 - 37P^3)(H_{req})$$

Equation 11

There *was* significant negative relationship ($p = 0.006$) between capacity/transport ratio and the drift length outputs produced by model 2 (Figure 15). The relationship between capacity/transport ratio and drift length in drift model 2 was best fit to an asymptomatic trend line. The standard error of the non-linear regression was $S = 4.037$, indicating that the predicted drift length values fell a standard distance of approximately ±4 m from the trend line.

When capacity/transport ratio (**Q_c/Q**) of fences was between 0 and 15:1 in drift model 2, drift length declined rapidly from 34 m - 8 m. When capacity/transport ratio was greater than 15:1 in drift model 2, drift length was less than 10 m. The overall trend in capacity/transport ratio versus drift length produced by drift model 2 met the expected outcome according to stages of drift formation in which drift length *decreases* with increasing capacity/transport ratio. The consistency of drift lengths below 10 m in drift model 2 indicates that fences with capacity/transport ratios greater than 15:1 likely do not exceed the first stage of drift formation (Figure 2), and the majority of seasonal snow transport is stored on the upwind side of the fence and in close proximity downwind of the fence. The variable of porosity is included in drift model 2 (equation 11), but porosity did not have a substantial effect on drift lengths, indicating

that capacity/transport ratio was the key variable influencing drift length for the fences and conditions investigated

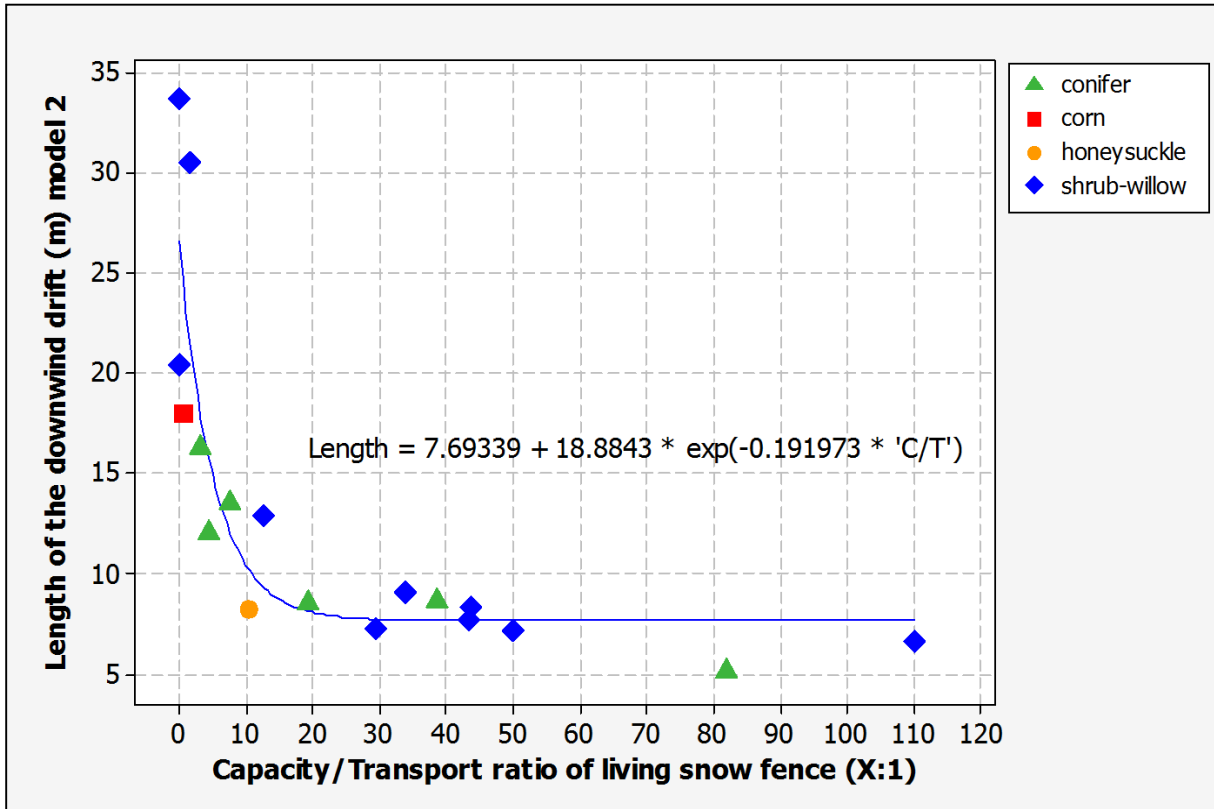


Figure 15: Capacity/Transport ratio (Q_c/Q) versus length of the downwind snow drift as predicted by drift model 2 for 18 living snow fences of various ages (years since planting) and species in New York State

Table 5: Summary of regressions, p values, r² values, and S values for all fences, shrub-willow fences, and conifer fences

	All Fences		Shrub-willow Fences		Conifer Fences	
Simple Linear Regressions (predictor versus response)	p	r ²	p	r ²	p	r ²
Age versus Height	<0.001	0.600	<0.001	0.852	0.149	-
Age versus Porosity	0.005	0.415	<0.001	0.892	0.877	-
Age versus Capacity	<0.001	0.562	0.001	0.769	0.090	0.554
	All Fences					
Non-Linear Regressions (predictor versus response)	p	S				
Capacity/Transport Ratio versus Drift Length (drift model 1)	0.136	-				
Capacity/Transport Ratio versus Drift Length (drift model 2)	0.006	4.037				

5 DISCUSSION

5.1 Functionality and Benefits of Living Snow Fences

Height and porosity are the key structural variables that influence snow trapping, the primary benefit of living snow fences. The time lag until height and porosity values equate to fully functional snow fences, where fence capacity is greater than or equal to average annual snow transport ($Q_c \geq Q$), is an important consideration in the use and design of living snow fences. The results of this study showed that the height and porosity of shrub-willow and conifer living snow fences in New York State was sufficient to create fully functional fences ($Q_c > Q$) three years after planting (Figures 8, 10, 11, 12). This result confirms Volk et al. (2006) which states that known shrub-willow growth rates and stem counts will produce functional snow fences 2 - 3 years after planting with proper establishment. Kuzovkina and Volk (2009) noted that rapid height growth and high branch density make shrub-willows ideal for living snow fences, and illustrated this with an age 3 shrub-willow fence that appeared to produce substantial snow trapping. However, these reports were primarily based on results from shrub-willow biomass studies and general observations, and were not quantified in the context of living snow fences.

The majority of literature states that living snow fences take five to seven years or longer to begin functioning (USDA 2012), and even longer to become fully functional ($Q_c \geq Q$). Living snow fences in the current study were fully functional at younger ages than what is commonly reported in the literature, due in part to light transport conditions across all 18 research sites. Sites with higher transport conditions may increase the time until fences become fully functional, such as Powell et al. (1992) in which living snow fences of various vegetation types in Wyoming took 20 years to becoming fully functional. The living snow fences in Powell et al. (1992) were

studied under transport conditions of approximately 100 t/m, which is approximately five to ten times the transport conditions estimated in the current study (Table 3). However, fence capacity (Q_c) was over 100 t/m for 11 snow fences investigated in the current study. All shrub-willow fences in the current study had capacity over 100 t/m by age 4, and conifer fences had capacity over 100 t/m by age 5. Eight fences in the current study had capacity large enough to be fully functional even in “severe” transport conditions of 160 – 320 t/m (Tabler 2003), and three of these fences had capacity enough to be fully functional in “extreme” transport conditions of >320 t/m, the maximum age (years since planting) of any fence in this study being 11. This indicates that plant selection, planting pattern, and other fence installation and management practices can reduce the time it takes for living snow fences to become fully functional, even in higher transport conditions of 100 t/m or more. Living snow fences therefore have the potential to become fully functional at ages much younger than what is commonly reported in the literature.

Tabler (1994) modeled the functionality of living snow fences over time under different transport conditions using the variables of height, porosity, and capacity. For two row conifer fences planted as *seedlings*, at 2.4 m plant and row spacing, Tabler (1994) estimated that under snow transport conditions of 20 t/m, fences would take six years to become fully functional. This transport quantity was only 1 t/m greater than the largest Q value observed in the current study, but fences in the current study were fully functional in half the time (age 3). For moderate snow transport conditions of 80 t/m, and severe conditions of 160 t/m, the estimated time until fences became fully functional was 10 and 14 years respectively (Tabler 1994). Fences in the current study achieved more capacity in less time, which emphasizes the influence of plant selection,

preventing animal browse (which can severely stunt young fences), and other best management practices, on the amount of time required for living snow fences to become fully functional.

Shrub-willow fences are likely to have more rapid growth rates and increase their capacity more quickly than the conifer fences in Tabler (1994), and conifer fences in general (Figure 8, Figure 11). Planting conifer fences with larger trees (as opposed to seedlings) will shorten the time until the fences become fully functional, but will also increase the cost of installation by using larger, more expensive planting stock and requiring more extensive work at the time of planting. Planting additional rows of conifers and/or planting conifers at smaller plant and row spacing will have the same effect by lowering optical porosity of the planting allowing fences to become functional more quickly, but also raising the cost of installation by increasing the total number of plants used per linear meter of fence. Shrub-willow fences can likely become fully functional in the shortest time period compared to other vegetation types, but without the increased costs associated with large potted trees, as a result of rapid grow rates, low cost of planting stock in the form dormant stem cuttings, and relative ease of planting (Heavey and Volk 2013b, Abrahamson et al. 2010). The rate of height growth and the rate of porosity exclusion of shrub-willow fences was more rapid and predictable than conifer fences in the current study (Figure 8, 10), which further supports the choice of shrub-willows for living snow fences, although planting patterns of conifer fences was more variable and the age of planting stock at installation was not known.

Implementing a suite of site preparation and best management practices can further improve the survival and growth rates of living snow fences and shorten the time it takes them to become

functional (Heavey and Volk 2013b). This includes techniques mentioned in previous publications (see Tabler 2003, Gullickson et al. 1999) that are still being actively developed and improved for living snow fences such as thorough site assessments including soil sampling; selection of species ideal for living snow fences and closely matched to site conditions; thorough site preparation techniques including the suppression of existing vegetation, soil preparations, and soil amendments; proper planting techniques for each vegetation type; prevention of browse by deer and other animals; and proper post-installation monitoring and maintenance for 2-3 years after planting to ensure that fences become established and achieve optimal growth rates (Heavey and Volk 2013b).

Proper installation and maintenance techniques can reduce the possibility of wasting time and resources on failed, partially functional, or slowly maturing fences; and maximize the long term economic benefits of living snow fences. The installation cost of shrub-willow fences is approximately \$12,000/km (Heavey and Volk 2013b). Walvatne (1991) reported the cost of installation contracts in Minnesota for living snow fences of various vegetation types to be between \$53,000/km and \$212,000/km (adjusted for inflation to 2013 dollars). Other living snow fence installation contracts have been reported at \$25,000/km in Iowa (Shaw 1989), and \$38,000/km in Colorado (Powell et al. 1992). By comparison, Powell et al. (1992) also reported the cost of large Wyoming structural snow fences 4.3 m in height to be \$68,000/km. When a *high* cost estimate for three years of all inclusive post-installation maintenance is added to the installation cost of shrub-willow living snow fences, the total cost per km is approximately \$21,000 (Heavey and Volk 2013b). This all inclusive cost for shrub-willow fences is less than all the estimates of installation costs for living snow fences above, and less than 1/3rd the

installation cost of Wyoming style structural fences which would provide similar snow catching capacities to a four or five year old shrub-willow fence.

If a 1 km shrub-willow fence in New York State prevented at least 10 spot-treatment cycles for snow and ice control of blowing snow annually, that fence would produce a positive net present value over a twenty year life cycle (Heavey and Volk 2013b). Preventing one accident and one road closure per year, in addition to these conservative values of snow and ice control savings, could produce net present values of approximately \$800,000 or more, benefit-cost ratios of 25:1, and payback periods as short two years after the fence becomes fully functional (Heavey and Volk 2013b). Thus living snow fences and shrub-willow fences in particular have excellent potential to produce benefit-cost ratios and net present values that exceed those reported by Daigneault and Betters (2000), and save a portion of the \$300 million spent annually on snow and ice control in New York State and the billions spent annually nationwide. Plant selection and best management practices can improve growth rates and reduce the time until fences become fully functional, further improving the economic performance of living snow fences.

Two potential drawbacks of using shrub-willow fences are that they require a relatively high degree of maintenance in the years immediately after planting, and may have shorter life cycles than conifer fences, potentially decreasing their benefit-cost ratios and net present values. An important factor in the economic feasibility of living snow fences is the amount of maintenance required in the years following installation (Tabler 2003). If living snow fences do not receive adequate maintenance immediately following installation, growth can be severely stunted. Stunted growth will increase the total maintenance costs by increasing the number of years

maintenance is needed, adding additional costs such as replanting, and increasing the time until fences become functional and begin producing snow and ice cost savings. Shrub-willows require full sunlight and intensive weed management to survive the first several growing seasons and achieve optimal grow rates (Heavey and Volk 2013b, Abrahamson et al. 2010). The early age of fully functional shrub-willow fences observed in the current study is not possible without proper monitoring and maintenance. Other shrub-willow living snow fences, not planted and maintained by SUNY-ESF, have been observed to be severely stunted from a lack of proper planting techniques and maintenance. Living snow fences planted with conifer *seedlings* may require similarly high levels of post-planting care to reduce weed competition for sunlight and physical resources, but conifer fences planted with larger potted or balled trees may require less post-planting care, potentially offsetting some of the costs associated with purchasing and installing larger trees.

Living snow fences are generally expected to have longer functional life cycles than structural snow fences, an important factor in their economic feasibility (Tabler 2003). Shrub-willows are known to be r-selected pioneer species (Kuzovkina and Quigley 2005) which may limit their functional life cycles as living snow fences, as a natural tradeoff to rapid juvenile growth rates and other r-selected traits that favor their use as living snow fences. Improved cultivars of shrub-willow have been developed primarily for woody biomass feedstocks that are generally harvested on a three year rotation cycle. Shrub-willow fences planted in open fields and left to grow well beyond the intended three year period *may* show different growth patterns than high density biomass plantings (Volk et al. 2006). This can lead to challenges to the long term functionality of living snow fence plantings such as early plant mortality, stunted growth,

large gaps in the fence, increased maintenance costs, increased susceptibility to a variety of disturbances, and generally reduced life cycles. All of these challenges can substantially reduce economic performance of shrub-willow fences, as well as fences of any other vegetation type or species. However, with a potential life cycle of 20 years or longer, and the full functionality and large amounts of excess storage capacity at early ages observed in this study, shrub-willow living snow fences should be able to produce favorable economic returns on investment *when best management practices are employed* (Heavey and Volk 2013a, 2013b).

If shrub-willow fences can become fully functional at early ages as observed in this study, a notable challenge to their long term survival is susceptibility to pests and diseases. This includes known susceptibility to a variety *Melampsora* rusts (Royle and Ostry 1995); cankers such as *Botryosphaeria* and other diseases (Kenaley et al. 2011); as well as Japanese Beetle, potato leaf hopper, and other pests (Cameron et al. 2010). Using disease and pest resistant cultivars and interplanting multiple cultivars will reduce the risk of catastrophic biological disturbances caused by pests and diseases in shrub-willow living snow fences. The chance of biological disturbance increases with time as the age of above ground biomass extends further beyond the intended three year harvest cycle, which remains the primary focus of shrub-willow breeding programs that are developing pest and disease resistant cultivars of shrub-willow (Smart and Cameron 2008).

The oldest shrub-willow fences investigated in this study in Preble, NY, showed signs of poor health and crown dieback at age 9, caused at least *in part* by an outbreak of *Cytospora* canker, likely in combination with the deleterious effects of installation practices and soil

conditions of these fences. The use of synthetic landscape fabric for weed control on these fences has proven to be a less than optimal management practice that can cause irregular and unhealthy root development, both above and below the fabric, as well as other detrimental effects on plants such as overheating young plants and girdling around the base of the plants as fences mature. Biodegradable landscape fabrics and fabric pins are therefore recommended for use in living snow fences (Heavey and Volk 2013b), and have been observed to be effective forms of weed suppression (in combination with other techniques) over the first two growing seasons for the two youngest shrub-willow fences investigated in this study. Other potentially effective forms of weed control for living snow fences that have not been extensively researched in this context are the use of cover crops, herbicides, mulches, mowing in close proximity to fence vegetation, and various combinations of these practices.

As with all living systems in nature, living snow fences will inevitably be subjected to some level of biological, chemical, and physical stressors and disturbances throughout their life cycles, threatening their long term functionality and economic performance. Living fences also possess some degree of resistance and resiliency, such as the excellent coppice ability of shrub-willows. This coppice ability employed in biomass production systems may be a means for regenerating shrub-willow living snow fences (and other coppice species) after disturbance, and generally extending the life cycle of fences in a way that would be less costly than removing and replanting them. Shrub-willow fences affected by disturbance can potentially be regenerated through coppicing *if* the disturbance is primarily restricted to the above-ground parts of the fence, leaving the root system mostly unharmed. If shrub-willow fences with a well established and *healthy* root system were coppiced in spring before bud-break, in conjunction with

suppression of surrounding vegetation and sufficient follow-up maintenance, up to 2 m or more in height growth in the following growing season could be achieved, potentially eliminating any gap in snow control after coppicing. Multiple rows of living fences or the use of temporary structural fences could also be used to prevent a lapse in snow control after coppicing, but this would further increase installation and maintenance costs. The use of coppicing for the regeneration of shrub-willow living snow fences, the continued research and development of pest and disease resistant cultivars, plant selection, planting patterns, and the choice of installation and management practices all have the potential to address these concerns, representing an area of future research for the improvement of shrub-willow fences and living snow fences in general.

Conifer living snow fences, in contrast to shrub-willows, are generally more K-selected climax species that may have much longer functional life cycles as living snow fences, potentially increasing their benefit-cost ratios and net present values. Conifer species in general, including some species investigated in this study, such as *Picea abies* and *Thuja occidentalis*, have been more widely tested as windbreaks and shelterbelts than shrub-willows, and have been proven capable of achieving functional heights and optical porosity values in ages beyond the 11 year chronosequence investigated in the current study (see Heisler and Dewalle 1998, Kenney 1985, Loeffler et al. 1992). Despite this larger body of research, no suitable conifer fences older than age 11 were identified for use in this study. A 31 year old planting of Norway spruce and white spruce was identified in the field from NYSDOT (2011), but it was unclear if this planting was originally *intended* as a living snow fence or simply functioned as one by chance. The plant spacing at this site was more than twice the largest observed plant spacing reported in this study at approximately 7.6 m and no evidence of thinning was apparent upon site investigation,

indicating that this planting would have likely taken many years to become functional. The age of this planting was also separated from the oldest fence investigated in this study by 20 years, nearly twice the total chronosequence of 11 years and 18 fences, so it was not further investigated as part of this study.

The anomaly of a 31 year old planting, and the maximum age of 11 for all fences investigated in this study, raises the question of why there appears to be a lack of conifer fences, or living snow fences of any vegetation type, in New York State older than age 11. A number of older fences are mentioned in the NYSDOT (2011) list of living snow fences (Appendix 3), but in general, these fences were not found to be clearly distinguishable in recent aerial photos nor definitively identifiable in the landscape upon site investigations. It is possible that these fences have not survived, have been intentionally or accidentally removed over the years, or have grown together with other naturally occurring vegetation in the landscape making them indistinguishable as unique instances of living snow fences. Furthermore, numerous fences of various vegetation types, *younger* than age 11, were listed in NYSDOT (2011), but were also not identifiable through aerial photos and site investigations, or had survival rates well below 75% upon site investigation, again emphasizing that plant selection and best management practices are important factors influencing the survival rates and functionality of living snow fences in New York State and beyond.

The corn and honeysuckle fences in this study were limited to one fence of each vegetation type, but the height growth and capacity of fences in this limited sample was notably less than shrub-willow and conifer fences. Corn fences are ultimately limited to the height and capacity

that can be achieved in one growing season. Sardinia-corn-1 also appeared to have been reduced from its full height (and capacity) by early winter 2012/2013 (Figure 16) when the fence was investigated, with the tops of the corn broken off or folded over, likely from a combination of weather conditions (rain saturation, snow loads, wind, freeze/thaw cycles, etc) and herbaceous plant characteristics (lack of woody tissue). Sardinia-corn-1 had less height than a corn fence investigated in Shulski and Seeley (2001) which was approximately 2 m in height prior to snow fall. After snow melt however, the height of this fence was reduced to approximately 1.2 m, indicating that corn fences may be unable to sustain their full height and capacity throughout the snow season, or even prior to sustained drift accumulation, due to a combination of weather conditions and herbaceous plant tissue. The outcome of this characteristic of vegetation type in the case of Sardinia-corn-1 was that the fence did not have enough storage capacity to be fully functional when combined with the non-porous 8 row planting configuration. A second strip of corn left standing at a distance of 50 m upwind or downwind of the first strip, as recommended by Tabler (2003), would have likely increased the storage capacity of this fence to fully functional levels ($Q_c > Q$) despite the reduced height, but would have also increased the (annual) cost of this fence.

The living snow fence Manheim-honeysuckle-8 had sufficient capacity to be fully functional under the estimated site transport, but was well below the trend in height and capacity amongst all fences, and above the trend in porosity. The fence also had a large bottom gap (Figure 38) due to the plant morphology, plant spacing, and single-row configuration. The observed bottom gap does not meet the desired morphological characteristic for living snow fences of a ground-level branching pattern, which may negatively impact the snow trapping function of this fence by

allowing wind and snow to pass through the bottom gap until it becomes filled in with snow. The 2.2 m height of Manheim-honeysuckle-8 was slightly *taller* than an age 3, two-row honeysuckle fence reported on in Shulski and Seeley (2001). Manheim-honeysuckle-8 was slightly *shorter* than a second age 3, single-row honeysuckle fence from Shulski and Seeley (2001), despite being five years older. The porosity of Manheim-honeysuckle-8 was 63%, which was slightly *lower* than the two-row honeysuckle from Shulski and Seeley (2001), and substantially *higher* than the single-row honeysuckle fence from the same study which was estimated at 20% porosity. The honeysuckle fences in Shulski and Seeley (2001) also had slightly larger plant spacing than Manheim-honeysuckle-8, and one was interplanted with red cedar 0.76 m in height. These fences are therefore not directly comparable to the results of the current study, but in general, honeysuckle appears to be a vegetation type that creates living snow fences with functional snow storage capacity in a reasonable time frame for light snow transport conditions, but with the potential for bottom gaps and high porosity if multiple rows are not used, and slower growth rates and lower capacities relative to shrub-willow and conifer fences.

5.2 Setback and Drift Length

Despite slight differences in the rate of height growth and porosity exclusion amongst different vegetation types, fences in this study had sufficient capacity to be considered fully functional ($Q_e > Q$) by age 3 (three years after planting), and continued to add excess capacity in a linear trend for the remaining 8 years of the chronosequence. It is presumable that these fences will also continue to add more height growth and excess capacity in future years, further increasing the observed capacity/transport ratios which were between 8:1 and 110:1 for fences

age 5 and older. These findings have important implications for the design of living snow fences in regards to drift length and the required setback distance which is driven by the interplay of height, porosity, and capacity/transport ratio (Tabler 2003).

The range of observed setback distances (**D**) in this study was three times the range of *predicted* setback values (**D₃₅**). This indicates that there is likely more variation than necessary in the setbacks observed in the field. This variation is likely due in part to site limitations, but also likely reflects the lack of consensus in the literature on how to determine a proper setback for living snow fences. The maximum observed setback distance was *twice* the maximum predicted value (**D₃₅**) (Table 4), indicating that some setback distances are excessively large since predicted setback (**D₃₅**) is a conservatively large estimate of setback that does not account for reduced drift lengths created by large capacity/transport ratios. There was no significant relationship between observed and predicted setback; nor between observed setback and height, capacity, or capacity/transport ratio; indicating that setback of living snow fences in New York State is not being consistently selected based on the model of predicted setback (Equation 9) from Tabler (2003), nor any other structural variable that would influence the length of the downwind drift. This again reflects the literature outside of Tabler (2003) which rarely provides the model of predicted setback, nor any other method for determining an appropriate setback distance for living snow fences. In some cases however, the setback of living snow fences in New York State is dictated by the available right of way space, the ability (or inability) to work with land owners to acquire additional planting space, and the presence of utilities or other features in the landscape that can limit planting space, further complicating the choice of setback and the interpretation of this data.

Land for living snow fences in New York State can be acquired under various existing mechanisms and programs of NYSDOT and other transportation agencies, but there is currently no statewide program designed *specifically* to assist transportation agency staff in working with land owners to acquire land for the purpose of living snow fences. There is also no statewide program for transportation agency staff to assist land owners in receiving conservation easements and payments for living snow fences, as has been developed in Minnesota and elsewhere (Wyatt 2012), potentially limiting the adoption of living fences in New York State. Living snow fences are eligible for various conservation easements programs and payments (NRCS 2007, USDA 2006, USDA 2012), representing an area for future research and improvement that may spur increased adoption of living snow fences in New York.

In many locations however, existing right of way space, which is often 10 m or more in New York State, may be sufficient to accommodate the entire length of the downwind drift on living snow fences based on the results of this study. The synopsis of living snow fence structure and function from Tabler (2003) provided in this study emphasized the influence of capacity/transport ratio on drift length in accordance with the stages of drift formation. The results of the current study showed that the capacity/transport ratios of living snow fences in New York State were between 8:1 and 110:1 in fences age five and older, indicating large amounts of excess storage capacity ($Q_c \gg Q$) at early ages. This high level of excess capacity is synonymous drifts that terminate in the early stages of drift formation, and drift lengths that are reduced to a fraction of their full equilibrium length of $35H$. Tabler (2003) is not explicitly clear as to whether drift model 1 (Equation 10), or drift model 2 (Equation 11) is the correct

interpretation of his model of drift length for living snow fences, so both possibilities were investigated in the current study.

Drift model 1 produced a series drift length values that was not significantly correlated with capacity/transport ratio, and did not produce the expected response of a negative relationship between the two variables. The drift lengths produced by model 1 were *larger* than the predicted setback (**D₃₅**) 78% of the time. This is the opposite of the expected result which should show a *reduced* drift length compared to the conservative predicted value (**D₃₅**) which does not account for the influence of capacity/transport ratio. The drift length values produced by model 1 are not logical when considered in context of the stages of drift formation relative to capacity/transport as ratio discussed in Tabler (2003), and reiterated in section 2.3 of the current study. When capacity/transport ratio was greater than 15:1 in drift model 1, drift length generally *increased* (Figure 14), producing illogical drift length outputs such as drifts 44 m in length when capacity/transport ratio was 50:1; and drifts 57 m in length when capacity/transport ratio was 110:1 (Table 4) under light snow transport conditions. Drift model 1 therefore *cannot* be considered a valid model of predicting drift length for living snow fences.

In contrast to drift model 1, *drift model 2* produced a logical series of outputs of drift length for the fences and conditions investigated in this study. In drift model 2, there *was* a significant negative relationship between capacity/transport ratio and drift length (Figure 15), as expected based on the work of Tabler (2003). The drift lengths produced by model 2 were *smaller* than the predicted setback 89% of the time, indicating the expected response to capacity/transport ratio in accordance with the stages of drift formation, in which drift length *decreases* in response

to increasing capacity/transport ratio. Drift model 2 is therefore the correct interpretation of Tabler (2003) based on the results of this study, and a valid model for estimating the drift length and appropriate setback distance of living snow fences of different heights, porosities, and capacity/transport ratios. The drift length values produced by model 2 are logical and consistent with the stages of drift formation described by Tabler (2003), in that very large capacity/transport ratios produce drift lengths that are substantially *smaller* than predicted setback values (D_{35}), indicating that excess capacity of the fence is correctly reducing the predicted length of the downwind drift, which is synonymous with termination of seasonal drift growth in the early stages of drift formation (Figure 2) as a result of excess storage capacity.

Drift model 2 showed that when capacity/transport ratio exceeds 15:1, drift length is always less than 10 m. If validated in future research, this is an important and impactful result for the design of living snow fences in New York State and beyond. When capacity/transport ratio exceeds 15:1 and drift length does not exceed 10 m (Figure 15). This is likely synonymous with the *first* stage of drift formation illustrated in Figure 2, where approximately 10% or less of the potential fence capacity is occupied by the seasonal transport at the site, and the length of the downwind drift is reduced to a fraction of the maximum 35H setback that is commonly prescribed in the literature. The final piece of this of this research to validate the predicted drift lengths of drift model 2 would be to monitor drift formation around living snow fences of known heights and porosities and compare predicted drift lengths from model 2 to *observed* drift lengths measured in the field. This task was originally included in the objectives of this study, but was not able to be accomplished due to frequent warming and rain events during the winter of

2012/2013 which essentially negated any sustained drift growth over the course of the snow season.

If validated with observed values, the data and calculations of this study, the observed capacity/transport ratios, and the predicted influence on drift length from drift model 2 can be easily incorporated into the analysis and design of living snow fences. This offers the potential of a much needed methodology for more precise selection of setback distances to replace the vague and inaccurate generalizations offered in the current literature, and the limited usefulness of the predicted setback model (D35). The trend of fence capacity observed in this study was shown to exceed snow transport at all sites after just three growing seasons, and increase capacity/transport ratios to levels of 100:1 or greater over the next eight years. For living snow fence design, drift model 2 can be used to estimate drift length and required setback distance for any fence of a known or estimated capacity/transport ratio. Likewise, the capacity/transport ratio and other variables of living snow fences of various vegetation types and ages can be estimated using the time series graphs and regression equations from this study, then applied to drift model 2 for design purposes. This would allow snow fence design teams to model the length of the downwind drift over time at different capacity/transport ratios, and select a setback distance that is most appropriate for the site conditions including available planting space and the long term snow and ice control goals of the site.

Using an even more general design approach, if the chosen species and planting pattern of a planned living snow fence is expected to produce a capacity/transport ratio greater than 15:1 in a reasonable time frame, any setback distance 10 m or greater could be assumed adequate to store

the estimated snow transport (Figure 15). This may allow the installation of living snow fences in many areas where substantial blowing snow problems exist, but available planting space is limited. Calculations of exceedance probabilities could also be easily incorporated into this methodology by simply using a design transport that is some multiple of the estimated site transport when determining the capacity/transport ratio. However, the large capacity/transport ratios observed in this study demonstrate that exceedance probabilities for living snow fences in New York State of common vegetation types such as shrub-willow and conifer fences may be somewhat of an unnecessary calculation, considering that a capacity/transport ratio of 2:1 is equivalent to a <0.1% exceedance probability (Tabler 2003), and this capacity/transport ratio is likely to occur very early in the fences life cycle under light transport conditions. Reduced setback distances may limit storage capacity and increase the exceedance probability during the early years of a living snow fence's life, but capacity would still be greater than zero even with a reduced setback, providing some level of passive snow control prior to the fence producing large capacity/transport ratios that compensate for the reduced setback distance. However, reduced setback distances could cause drifts around the fence to form on the roadway prior to large capacity/transport ratios being achieved, representing a potential hazard to drivers and a serious safety consideration. The influence of capacity/transport ratios on exceedance probabilities should therefore be considered another important area of future research for living snow fences. The influence of site topography is also an important consideration in the design of living snow fences which can limit or increase the snow storage capacity of the fence and influence the choice of setback distance.

5.3 Limitations of this Study and Future Research

Other limitations and assumptions of this study must also be considered when conducting future research, and before and applying the results of this study to the design of living snow fences in the field. This study was conducted with the sole the intention of investigating the physical structure and snow trapping function of living snow fences in *New York State*, based on climatic variables and models developed specifically for New York. Some results of this study *may* be applicable to other states and regions where similar conditions and snow fence practices exist, but other regions may have different conditions and the results of this study may not apply. Errors in judgment or calculations of living snow fence design can threaten road safety and increase snow control costs. Further research should validate the results of this study before design implications offered here are put into practice in New York State, and especially outside of New York State.

The estimates of snow transport in this study were modeled using the key assumptions of the relocation coefficient (C_r) at all sites being equal to the statewide average of 0.17 provided by Tabler (2000); fetch area at all sites being measured at a perpendicular angle to the fence; Tabler's (2000) model of snowfall over the drift accumulation season (Equation 5); and assumptions of what does and does not constitute wind obstructions that would cause snow deposition and limit the size of the fetch. Actual relocation coefficients, fetch distances, snowfall totals, and snow transport quantities may be higher or lower at each site than what was estimated in this study. However, even if all the transport values estimated in this study were *doubled* as a result of increased relocation coefficients, larger fetch distances and/or other factors, the severity of snow transport conditions would still be classified as "light moderate" (20 - 40 t/m) by Tabler (2003). The assumed relocation coefficient (C_r) of 0.17 provided by Tabler

(2000) for New York differed considerably from other studies conducted in Minnesota ($C_r = 0.35$) (Shulski and Seeley 2001), and Siberia ($C_r = 0.70$) (Komarov 1954).

Relocation coefficient can also vary in specific locations across one region based on the water content of snowfall, speed and direction of wind, topography, and other climatic conditions and physical features of each individual site (Tabler 2003). If the C_r value was approximately doubled in the current study to 0.35 as reported in Shulski and Seeley (2001), mean snow transport across all sites would increase from 9 t/m to 18 t/m, ranging from 5 t/m to 40 t/m; but the severity classification of all sites would still be light-moderate (Tabler 2003). The mean capacity/transport ratio would be reduced by approximately half from 27:1 to 13:1. Conifer fences would still be fully functional three years after planting however, and willow fences would be fully functional by age 4, one year later than reported. After age 4, capacity/transport ratios would be in the range of 4:1 to 54:1 by age 11 or earlier, which is still substantial amounts of excess storage capacity at young ages.

Tabler (2003) states that C_r values are generally between 0.20 and 0.30 in the North Eastern United States, but Tabler (2000) reported values in New York State that were both higher and lower based on in-depth climatological studies using data from weather stations across the state, long term climate data, and several climate models. Sites with larger fetch distances will increase the importance of relocation coefficient, and estimates of snow transport will be more sensitive to the relocation coefficient on sites with larger fetch distances. It is therefore recommended that a thorough climatic study be undertaken in each region where living snow fences are put into practice to determine a relocation coefficient for each living snow fence

design project as accurately as possible. An excellent methodology and several case studies for achieving this is provided in Shulski and Seeley (2001).

Another notable limitation of the current study is that only fences that could be identified through a combination of remote sensing and field investigations were measured and reported on. This represents a bias for sites that likely had superior plant selection, site quality, planting techniques, and post-planting care. The reported rates of height growth, porosity exclusion, and increasing capacity are therefore likely to be high estimates of what can be expected from all sites and fences across New York State. However, the observations of this study, and perhaps even more ideal outcomes for living snow fences, *should* be obtainable for most new living snow fence installations when proper site analysis, design, plant selection, planting patterns, installation and management practices are employed (see Heavey and Volk 2013b). There are at least 15 fences that have achieved functional capacity/transport ratios in New York State, but also an equal or greater number of fences (or sections of fences) that have struggled to thrive or completely failed, again stressing the importance and need for best management practices.

Additionally, New York State has plentiful precipitation, fertile soils, and other generally favorable growing conditions for living snow fences, allowing trees and shrubs to grow relatively quickly compared to the maximum growth rates that may be achievable in other regions. This may reduce capacity/transport ratios and increase the time until fences become full functionality in other regions, although the majority of shrub-willow cultivars and conifer species recommended for living snow fences (Heavey and Volk 2013b) can grow effectively over a wide geographical range and tolerate a variety of site conditions. Other species suitable for living

snow fences can also be matched to site conditions in different regions. Species such as honeysuckles, traditionally bred for ornamental purposes, may have less tolerances for adverse conditions, may be less widely adaptable, and may have less range and more limited application as living snow fences. More snowfall over the drift accumulation season, higher relocation coefficients, and larger fetch distances as observed in other regions such as the Western and Midwestern United States (Tabler 2003) would also reduce capacity/transport ratios, increase the time until fences become fully functional ($Q_c \geq Q$), and possibly never allow fences to reach capacity/transport ratios of 15:1 or greater in which downwind drift length is drastically reduced.

Finally, the winter of 2012/2013 produced frequent temperature spikes well above 0° C across New York State, as well as sporadic rain events. Freeze/thaw cycles and rain events may be another important factor influencing sustained drift growth over the drift accumulation season, and is potentially an important limiting factor of the drift sizes and lengths that occur around living snow fences in New York State. These conditions essentially eliminated the possibility of collecting useful data on snow quantities and downwind drift lengths in 2012/2013 around the living snow fences investigated in this study, but some *limited* data was collected, and limited amounts of other data is available from previous studies. Small snow drifts were measured around living snow fences Tully-willow-4, Preble-willow-9, Columbia-conifer-3, and Manhiem-honeysuckle-8 in late February 2013, but snow deposition around the fences was negligible, estimated at substantially less than 1 t/m in all cases. The maximum height of drifts around these fences was approximately 0.3 m and the maximum length of discernible downwind drifts was approximately 2 m. An image of these small drifts around living snow fence Manheim-honeysuckle-8 is provided in Figure 39.

Drift measurements taken on living snow fence Tully-willow-4 in 2011, two years after the fence was planted, reported a snow drift with a maximum depth of 1.3 m that terminated at a length of 3.5 m downwind (unpublished data), but the accuracy completeness of this data is unverified. Previous studies have modeled the length of the downwind drift on scale models of living snow fences (Sturges 1984, Peterson and Schmidt 1984), but the relevance of these studies is limited by the fact that scale models fill to maximum capacity very quickly due to their small size, and the reported drift lengths generally represent full capacity equilibrium drifts and do not provide useful data in regards to the influence of capacity/transport ratio on drift length.

A 1998 study in France by Naaïm-Bouvet and Mullenbach reported snow data on two spruce living snow fences planted at 1 m spacing, approximately 1.7 m in height and 35% porosity, which would be equivalent to a capacity (Q_c) of 23 t/m. Exact transport values were not reported, but 20 m² of snow was reported in the cross-sectional area downwind drift, which would be between approximately 3 t/m (0.10 water equivalent) and 16 t/m (0.70 water equivalent) of snow transport depending on the water equivalent of snow in the drift at the time of measurement based on the degree of melt and the densification of snow under its own weight. This indicates that the overall capacity/transport ratio of these fences was likely greater than 1:1 ($Q_c > Q$). The drifts on these fences were reported to be approximately 28 m long, with the majority of deposition occurring within 20 m downwind.

The most complete analysis of snow deposition and downwind drift lengths on living snow fences comes from Shulski and Seeley (2001) who reported estimated capacity, observed

transport, and observed drift lengths for three living snow fences in Minnesota. A standing corn fence in this study, approximately 2 m in height with a capacity/transport ratio of 2.5:1, produced a downwind drift 27 m in length. Two honeysuckle fences of similar heights and capacity/transport ratios also produced drift 27 m in length. This is consistent with the drift length outputs of drift model 2 (Figure 15), when capacity/transport ratio is greater than 1:1 but less than 15:1, and drift length is still declining rapidly in response to increasing capacity/transport ratio. It is notable that for the five fences reported in Naaim-Bouvet and Mullenbach (1998) and Shulski and Seeley (2001), drift length never exceeded 17H, or 17 times the reported height of the fence; less than half of the 35H commonly recommend as a setback standard in the literature on living snow fences.

Despite the limitations of this literature on drift lengths around living snow fences, it does appear to verify the general finding of the current study that, when capacity/transport ratio of living snow fences exceeds 1:1 ($Q_c > Q$), fences can be situated closer to roadway than the 30 m - 180 m or more, or 35H, prescribed in the current literature. A thorough study conducted throughout the course of a snow accumulation season(s) on various living snow fences, with the intention of validating the capacity/transport ratios and drift length outputs of drift model 2 reported in this study is the most pertinent future research to that should follow. The research sites used in this study could be a basis for future measurements since their survival and accessibility has already been confirmed, and this set of research sites could be supplemented with additional living snow fences. Other areas of future research should include repeating the methods of this study on more vegetation types and species; repeating the methods of this study on fences with ages beyond the 11 year chronosequence examined in this study; and repeating

the methods of this study in other regions where climatic and growing conditions are both similar and different.

6 CONCLUSION

Living snow fences can reduce the cost of highway maintenance and improve highway safety by disrupting wind patterns and causing controlled deposition of blowing snow in drifts before it reaches the roadway. The key structural variables influencing the snow trapping function of living snow fences are height and optical porosity. This study measured height and porosity on a stratified sample of 18 living snow fences of various ages (years since planting) and vegetation types in New York State. This data was analyzed using the models of Tabler (2000 and 2003) to estimate and interpret the snow trapping function of the fences. Height and capacity of fences increased linearly with increasing age as expected. Shrub-willow fences increased in height and capacity at a slightly faster rate than the trend amongst all fences. Porosity of fences decreased linearly with age as expected, with shrub-willow fences decreasing at a slightly slower rate than the trend amongst all fences. The estimated snow transport quantities at all sites was classified as very light to light (<20 t/m). Three years after planting, fence capacity was greater than the observed transport at each respective site, indicating that fences were fully functional at ages much earlier than what is commonly reported in the literature. For all fences age five and older, capacity/transport ratios were between 8:1 and 110:1. This substantial amount of excess storage capacity was expected to reduce the length of the downwind drift based on the stages of drift formation described by Tabler (2003) and reexamined in this study.

Two models of drift length were investigated, and drift model 2 was found to be a valid model for predicting the influence of capacity/transport ratio on drift length in accordance with the stages of drift formation. This model, which used the required fence height as a coefficient for expressing drift length in units of meters, consistently predicted drift lengths less than 10 m

when capacity/transport ratios exceeded 15:1. These drift lengths are much smaller than the setback distances commonly recommended in the literature, and setback distances observed in the field in this study. If this result can be validated in future studies, it can be easily incorporated into the design of living snow fences to more accurately select appropriate setback distances based on predicted drift lengths as influenced by capacity/transport ratios. This would be a significant contribution to literature, which currently provides no consensus or precise methodology for modeling and selecting appropriate setback distances for living snow fences. This result may also allow more living snow fences to be installed in areas where there are substantial blowing snow problems, but limited right of way space for planting. The time-series graphs and regression equations produced in this study also have the potential to be useful design tools for modeling living snow fence structure and function at various ages. The survival and time until living snow fences become fully functional is highly dependent on proper plant selection and best management practices, which can heavily influence the economic performance and feasibility of living snow fences.

Additional research should be conducted to validate the findings of this study before applying the results to living snow fence design in the field, since living snow fences can have important and substantial impacts on road safety and the cost of highway maintenance. Critical assumptions of this study were primarily related to climatic variables such as the relocation coefficient of snowfall, and the prevailing wind direction which affected the measurement of fetch distances. Future research should repeat the methods of this study using fences of the same and different species, ages, and locations; and also seek to validate the predictions of snow transport quantities, snow fence capacities, and predicted drift lengths of drift model 2 by

measuring snow drifts around living snow fences throughout the course of a snow season and over multiple snow seasons.

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Appendix 1 – English Unit Tables

Table 6: English Units - Taxonomy and planting pattern of 18 living snow fences sampled in this study, sorted by vegetation type and age

Fence ID Tag (Town - vegetation type - age)	Scientific Name	Common Name	Fence Length (ft)	Plant Spacing (ft)	Number of rows	Row Spacing (ft)	Fetch Distance (ft)
Sardinia - corn - 1	<i>Zea mays</i>	standing corn rows	1148	4"	8	2' 6"	1115
Manheim - honeysuckle - 8	<i>Lonicera tatarica</i>	Arnold red honeysuckle	594	3'	1	-	676
Paris - willow - 1	<i>Salix purpurea, Salix miyabeana</i>	var. SX64, Fishcreek	377	2'	2	2' 6"	902
Beerston - willow - 2	<i>Salix miyabeana, Salix purpurea</i>	var. SX64, Fishcreek	1345	2'	2	2' 6"	420
Hamburg - willow - 3	<i>S. sachalinensis, S. dasyclados</i>	var. SX61, 98101-61	866	2'	2	2' 6"	2559
Tully A - willow - 4	<i>Salix miyabeana, Salix purpurea</i>	var. SX64, Fishcreek	1581	2'	2	2' 6"	2461
Tully B - willow - 6	<i>Salix caprea hybrid</i>	var. S365	771	2'	2	2' 6"	607
Tully C - willow - 6	<i>S. sachalinensis x S. miyabeana</i>	var. Sherburne	771	2'	2	2' 6"	607
Grand Gorge - willow - 7	<i>Salix purpurea</i>	shrub-willow purpurea	518	1'	1	-	561
Preble A - willow - 9	<i>S. miyabeana, S. sachalinensis</i>	var. SX64, SX61, 98101-61, 9870-42	630	2'	2	2' 6"	1575
Preble B - willow - 9	<i>S. miyabeana, S. sachalinensis</i>	var. SX64, SX61, 98101-61, 9870-42	377	2'	2	2' 6"	1214
Preble C - willow - 9	<i>S. miyabeana, S. sachalinensis</i>	var. SX64, SX61, 98101-61, 9870-42	381	2'	2	2' 6"	1765
Columbia - conifer - 3	<i>Picea abies</i>	Norway spruce	220	10'	3	7'	2805
Chautauqua - conifer - 4	<i>Picea pungens</i>	blue spruce	607	12'	3	10'	2034
Pomfret - conifer - 5	<i>Picea pungens</i>	blue spruce	459	12'	2	10'	1434
Spencerport - conifer - 6	<i>Pseudotsuga menziesii</i>	Douglas-fir	1224	6'	1	-	515
Gabriels - conifer - 8	<i>Thuja occidentalis</i>	northern white cedar	1132	7'	1	-	1542
Cobleskill - conifer - 11	<i>Abies concolour</i>	white fir	991	10'	2	10'	1043
Mean 5.7	-	-	778	4' 3"	2	4' 4"	1325
Median 6.0	-	-	771	2'	2	2' 7"	1214
Standard Deviation 3.0	-	-	384	4'	1.6	3' 3"	755

Table 7: English Units - Summary of results for variables related to snow trapping function of 18 living snow fences of various species in New York State, sorted by vegetation type and age

	H_{req}	H	P	Q_c*	Q*	Q_c/Q*
Fence ID Tag (Town - Vegetation Type - Age)	Required Height (ft)	Observed Height (ft)	Porosity	Capacity (tons/ft)	Transport (tons/ft)	Capacity/Transport Ratio
Sardinia - corn - 1	3'	4' 3"	0%	1	2	<1
Manheim - honeysuckle - 8	2' 7"	7' 3"	63%	16	2	10
Paris - willow - 1	3' 3"	4' 11"	92%	<1	3	<1
Beerston - willow - 2	2'	6' 3"	88%	<1	1	<1
Hamburg - willow - 3	5'	7' 6"	77%	10	6	1.5
Tully A - willow - 4	4'	12' 10"	52%	56	4	13
Tully B - willow - 6	2' 3"	10' 10"	61%	38	1	30
Tully C - willow - 6	2' 3"	13' 10"	62%	65	1	50
Grand Gorge - willow - 7	2' 3"	19' 4"	47%	138	1	110
Preble A - willow - 9	3'	16' 5"	33%	80	2	34
Preble B - willow - 9	3' 3"	19' 4"	39%	130	3	44
Preble C - willow - 9	3' 7"	23'	26%	144	3	43
Columbia - conifer - 3	4' 3"	9' 6"	27%	22	5	4
Chautauqua - conifer - 4	4"	6' 11"	61%	13	4	3
Pomfret - conifer - 5	3"	11' 10"	41%	44	2	19
Spencerport - conifer - 6	2' 3"	18' 4"	29%	94	1	82
Gabriels - conifer - 8	4' 7"	11' 10"	39%	43	6	8
Cobleskill - conifer - 11	3' 3"	17' 5"	38%	100	3	39
Mean	3' 3"	12' 6"	50%	62	3	27
Median	3' 3"	11' 10"	50%	56	3	16
Standard Deviation	1'	5' 7"	20%	47	2	31

Note* - The **Q_c** and **Q** values reported in this table were rounded to the nearest ton/ft (short ton per linear foot) for clarity. The capacity/transport ratios (**Q_c/Q**) reported in this table are the rounded ratios of the *actual* capacity and transport values, the same as reported in Table 3

Table 8: English Units - Observed setback, predicted setback, and models of drift length of 18 living snow fences of various species in New York State, sorted by vegetation type and age

Fence ID Tag (Town - Vegetation Type - Age)	Observed Setback Distance (D) (ft)	Predicted Setback Distance (D ₃₅) (ft)	Predicted Drift Length Model 1 (ft)	Predicted Drift Length Model 2 (ft)	Capacity/Transport Ratio (Q_c/Q)
Sardinia - corn - 1	233	95	82	59	<1
Manheim - honeysuckle - 8	125	79	82	26	10
Paris - willow - 1	85	98	171	112	<1
Beerston - willow - 2	89	59	223	66	<1
Hamburg - willow - 3	92	151	154	98	1.5
Tully A - willow - 4	138	125	135	43	13
Tully B - willow - 6	33	72	112	23	30
Tully C - willow - 6	33	72	144	23	50
Grand Gorge - willow - 7	312	72	187	23	110
Preble A - willow - 9	43	108	141	30	34
Preble B - willow - 9	33	95	177	26	44
Preble C - willow - 9	30	105	174	26	43
Columbia - conifer - 3	171	135	92	39	4
Chautauqua - conifer - 4	194	121	92	52	3
Pomfret - conifer - 5	102	92	112	30	19
Spencerport - conifer - 6	121	69	144	16	82
Gabriels - conifer - 8	56	141	118	46	8
Cobleskill - conifer - 11	135	98	157	30	39
Mean	<i>112</i>	<i>98</i>	<i>138</i>	<i>43</i>	<i>27</i>
Median	<i>102</i>	<i>98</i>	<i>141</i>	<i>30</i>	<i>16</i>
Standard Deviation	<i>79</i>	<i>26</i>	<i>39</i>	<i>26</i>	<i>31</i>

Appendix 2 – Photos of Living Snow Fences



Figure 16: Living snow fence Sardinia-corn-1 from the windward side of the fence in winter 2012/2013



Figure 17: Living snow fence Sardinia-corn-1 from the leeward side of the fence in winter 2012/2013



Figure 18: Living snow fence Paris-willow-1 (SX64, Fishcreek) in winter 2012/2013



Figure 19: Living snow fence Paris-willow-1 in early spring 2013



Figure 20: Living snow fence Beerston-willow-2 (SX64, Fishcreek) in late summer 2012



Figure 21: Living snow fence Beerston-willow-2 in winter 2012/2013



Figure 22: Living snow fence Columbia-conifer-3 (Norway spruce) from the windward side in Fall 2012



Figure 23: Living snow fence Columbia-conifer-3 in winter 2012/2013



Figure 24: Living snow fence Hamburg-willow-4 (SX61, 98101-61) from the leeward side in late summer 2012



Figure 25: Living snow fence Hamburg-willow-4 from the windward side in winter 2012/2013



Figure 26: The author on the leeward side of living snow fence Tully-A-willow-4 in winter 2012/2013



Figure 27: Side angle view of living snow fence Tully-A-willow-4 in August, 2012



Figure 28: Side angle view of living snow fence Chautauqua-conifer-4 (blue spruce)



Figure 29: Living snow fence Chautauqua-conifer-4 from the leeward side



Figure 30: Perpendicular view of living snow fence Pomfret-conifer-5 (blue spruce) from the leeward side



Figure 31: Side angle view from the center of living snow fence Pomfret-conifer-5



Figure 32: Optical porosity photo sample from living snow fence Tully-B-willow-6 showing stem morphology of shrub-willow variety S365



Figure 33: Optical porosity photo sample from living snow fence Tully-C-willow-6 showing stem morphology of shrub-willow variety Sherburne



Figure 34: Wide angle view of living snow fence Spencerport-conifer-6 (Douglas fir) from the windward side



Figure 35: Living snow fence Spencerport-conifer-6 from the edge of Rt. 531



Figure 36: Living snow fence Grand-Gorge-willow-7 from the leeward side in fall 2011



Figure 37: The author in front of living snow fence Grand-Gorge-willow-8 in winter 2012/2013



Figure 38: Living snow fence Manheim-honeysuckle-8 in late fall 2012



Figure 39: Small snow drifts formed around living snow fence Manheim-honeysuckle-8 in winter 2012/2013



Figure 40: Living snow fence Gabriels-conifer-8 (northern white cedar) in late fall 2012



Figure 41: Wide angle view of living snow fence Gabriels-conifer-8 in late fall 2012



Figure 42: Living snow fence Preble-A-willow-9 from the edge of I-81 SB in late summer 2012



Figure 43: Canopy photo of living snow fence Preble-A-willow-9 in late summer 2012



Figure 44: Wide angle view of living snow fence Preble-B-willow-9 from the edge of I-81 SB in summer 2012



Figure 45: Living snow fence Preble-B-willow-9 in winter 2012/2013



Figure 46: Perpendicular view of living snow fence Preble-C-willow-9 in July, 2012



Figure 47: Living snow fence Preble-C-willow-9 from the windward side in winter 2012/2013



Figure 48: Perpendicular view of living snow fence Cobleskill-conifer-11(white fir) in winter 2012/2013



Figure 49: Wide angle view of living snow fence Cobleskill-conifer-11 in fall 2011

All Photos by Justin P. Heavey

Appendix 3 – NYSDOT List of Living Snow Fences

Table 9: NYSDOT (2011), list of state-wide living snow fence locations
 Reproduced with permission from NYSDOT, formatting and some text adapted for clarity

Existing Living Snow Fence Locations									
Residency	County	Town	Highway	Direction	MM Start	MM End	Vegetation type	Year installed	Length (miles)
Region 1									
Essex	None	Keene	73	EB			evergreens	2009	0.10
Schenectady	Schenectady	Duanesburg	I-88	EB &WB	160 81089		see note w		1.00
Region 1 subtotal									1.10
Region 2									
Herkimer	Herkimer	Manheim	167	S.B.	1.67E+10	1.67E+10	Norway Spruce	1982	0.20
	Herkimer	Manheim	167	S.B.	1.67E+10	1.67E+10	Honeysuckle	2005	0.20
Region 2 subtotal									0.40
Region 3									
Cortland/Tompkins	Cortland	Preble	I-81	SB	81I 3202 3094	81I 3202 3078	Willow	2005	1.60
	Cortland	Marathon	I-81	SB	81I 3202 1019	81I 3202 1000	Evergreen	1999	1.90
Onondaga East	Onondaga	Tully	North Rd	SB			Corn	2005	
Onondaga East	Onondaga	Tully	I-81	SB	81I 3303 1020	81I 3303 1000	Willows	2009	0.20
Region 3, subtotal									3.70
Region 4									
Livingston	Livingston	Avon	390	SB	~390I 4202 1332	~390I 4202 1329	Evergreens	2008	0.30
	Livingston	Groveland	390	SB	~390I 4202 1118	~390I 4202 1114	Evergreens	2009	0.40
Monroe West	Monroe	Spencerport	531	EB	~531 4301 2402	~531 4301 2046	white spruce	2007	4.40
	Monroe		I-390	SB			evergreens & decid.	1979	
Wayne/Ontario	Ontario	Naples	21	SB	~21 4403 1003	~21 4403 1000	corn 07-08	2007	0.30
Region 4, subtotal									5.40
Region 5									
Chautauqua	Chautauqua	Chautauqua	394	EB	17 5201 1055	17 5201 1059	Pine Trees	2009	0.40
Chautauqua	Chautauqua	Westfield	394	EB	17 5201 1038	17 5201 1040	Pine Trees	2009	0.20
Chautauqua	Chautauqua	Chautauqua	430	EB	17 5201 1115	17 5201 1117	Pine/Stick Tree's	2006	0.20
Chautauqua	Chautauqua	Chautauqua	430	WB	17 5201 1090	17 5201 1093	Standing corn	yearly	0.30
Chautauqua	Chautauqua	Sherman	430	WB	430 5201 1111	430 5201 1109	Standing corn	yearly	0.20
Chautauqua	Chautauqua	Pomfret	Route 60	SB	60 5201 3244	60 5201 3243	Colorado Spruce	2008	0.10
Erie North	Erie	Amherst	I-290	EB	290 5301 1091	2905301 1093	Evergreens	1997?	0.20
Erie North	Erie	Amherst	I-290				Rhus Sumac	2009	
Erie South	Erie	Boston	Rte. 219	NB Off ramp	219 5312 1231	219 5312 1232	Deciduous Shrubs	1993	0.10
Erie South	Erie	Boston	Rte. 219	SB	219 5312 1149	219 5312 1151	Decid Trees/Shrubs	1993	0.20
Erie South	Erie	Boston	Rte. 219	SB	219 5312 1141	219 5312 1143	Decid Trees/Shrubs	1993	0.20

Erie South	Erie	Boston	Rte. 219	SB	219 5312 1139	219 5312 1141	Evergreens	1993	0.20
Erie South	Erie	Boston	Rte. 219	SB	219 5312 1129	219 5312 1132	Decid Trees/Shrubs	1993	0.30
Erie South	Erie	Boston	Rte. 219	SB	219 5312 1126	219 5312 1127	Decid Trees/Shrubs	1993	0.10
Erie South	Erie	Boston	Rte. 219	SB	219 5312 1118	219 5312 1122	Decid Trees/Shrubs	1993	0.40
Erie South	Erie	Boston	Rte. 219	SB	219 5312 1116	219 5312 1119	Decid Trees/Shrubs	1993	0.30
Erie South	Erie	Boston	Rte. 219	SB	219 5312 1127	219 5312 1128	Decid Trees/Shrubs	1993	0.10
Erie South	Erie	Boston	Rte. 219	SB	219 5312 1120	219 5312 1123	Decid Trees/Shrubs	1993	0.30
Erie South	Erie	Boston	Rte. 219	SB			Willows	2010	
Erie South	Erie	Concord	Rte. 219	SB	219 5312 1044	219 5312 1046	Evergreens	1993	0.20
Erie South	Erie	Concord	Rte. 219	SB			Willows	2010	
Erie South	Erie	Collins	Rte. 39		62 5303 1022	62 5303 1023			0.10
Erie South	Erie	Hamburg	Rte. 75		75 5301 1208	75 5301 1209			0.10
	Erie	Hamburg	Rte. 5	interchange	5 5302 1195	5 5302 1197			0.20
Region 5, subtotal									4.40
Region 6									
Allegany West	Allegany	Friendship	I-86	Median	17 6103 2140	17 6103 2150	Conifer	2006	1.00
		West Almond	I-86	Median	17 6103 2140	17 6103 2150	Conifer	2007	
		Angelica	I-86	Median	17 6103 2140	17 6103 2150	Conifer	2008	
Steuben	Steuben	Campbell	I-86	Median	17 6404 4353	17 6404 4354	willows	2004	0.10
Schuyler/Yates	Schuyler	Dix	414	SB	414 6303 1096	414 6303 1098	ornamental shrubs	2006	0.30
	Yates	Potter	247	NB	247 6601 1008	247 6601 1010	Willows	2003	0.20
	Yates	Benton	14A	SB	14A 6604 1211	14A 6604 1213	Willows	2002	0.20
	Yates	Benton	14A	SB	14A 6604 1222	14A 6604 1224	willows/raspberry	2004	0.20
	Yates	Benton	Route 54	SB	54 6602 1128	54 6602 1130	Willows	2004	0.20
Region 6, subtotal									2.20
Region 7									
Clinton	Clinton		I-87	WB			Conifer	2009	
Franklin	Franklin	Gabriels	Route 86	left	86 7201 1047	86 7201 1048	Conifer	2005	0.10
				right	86 7201 1047	86 7201 1046			0.10
				left	86 7201 1045	86 7201 1043			0.20
				right	86 7201 1043	86 7201 1041			0.20
				left	86 7201 1040	86 7201 1042			0.20
Lewis	Lewis	Pinckney	177	N side	177 7402 1063	177 7402 1065	Willows	2002	0.20
	Lewis	Pinckney	177	S side	177 7402 1054	177 7402 1054	Willows	2002	0.10
	Lewis	Copenhagen	Route 12	SB	12 7405 7404	12 7405 7406	Willows	2007	0.20
Region 7, subtotal									1.30
Region 8									
Columbia	Columbia	Kinderhook	9H		9H81011153	9H81011154	Shrubs	2006	0.10
	Columbia	Stockport	9		9.81E+08	9.81E+08	Pine Trees	2005	0.10
	Columbia	Greenport	23/9 Inter.		2.38E+09	9.81E+08	Pine Trees	2006	0.80
Dutchess South	Dutchess	Wappinger	Route 9	SB	9.82E+08	9.82E+08	Pine trees	2006	0.20
Ulster	Ulster	New Paltz	208	SB	2.09E+10	2.09E+10	Standing corn	annual	0.10

	Ulster	Shawangunk	208	SB	2.09E+10	2.09E+10	Standing corn	annual	0.20
	Ulster	Hurley	209	SB	2.1E+10	2.1E+10	Standing corn	annual	0.20
Region 8, subtotal									1.70
Region 9									
Broome	Broome	Whitney Point	I-81	median	81I 9101 3199	81I 3202 1000	Conifer & dec trees	2003	19.90
Broome	Broome	Whitney Point	I-81	SB	81I 9101 3200 R	81I 9101 3199 R	Conif & dec shrubs	2006	0.20
Delaware South	Delaware	Walton	Route 10	EB			willows & shrubs	2011	0.50
Schoharie/Del N.	Delaware	Grand Gorge	Route 30	SB	30 9502 1010	30 9502 1015	Willows	2006	0.50
Schoharie/Del N.	Schoharie	Cobleskill	I-88	WB	88I 9507 1081	88I 9507 1080	Conifers	2002	0.10
Sullivan	Sullivan	Thompson	Route 42		42 9602 1089	42 9602 1089	Conifers	2007	0.10
Subtotal, Region 9									21.30
Region 10									
Suffolk East	Suffolk	Brookhaven	Route 27	EB	27-0705-1380	27-0705-1380	Conifers/RT Dogwood	2006	
	Suffolk	Riverhead	I-495	EB	495-0703-1403	495-0703-1404	Conifers/Cedars		0.10
Nassau South	Nassau	Hempstead	Ocean Pkwy	WB	909D03011021	909D03011018	Wild rose	2007	0.30
Region 10 subtotal									0.40
Statewide total									41.90

Note W Species on I-88 include privet (146), Streamco willows (146), purpleosier willow (146), arrowwood viburnum (194), blackhaw viburnum (108)
146 vanhoutte spirea, 146 common lilac, 146 nannyberry viburnum, 146 shadblow serviceberry, 146 "Mareiesii" doublefile viburnum,
146 European cranberrybush viburnum, 146 each of silky and grey dogwood and 146 winterberry.

Note X summersweet, sweetspire, white spruce, douglas fir, blue spruce