STRUCTURE AND FUNCTION OF LIVING SNOW FENCES IN NEW YORK STATE

by

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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.

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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
$\mathbf{C_r}$	Relocation coefficient, fraction of fallen snow relocated by the wind	none
$\mathbf{H_{req}}$	Required fence height	m
$\mathbf{Q_c}$	Snow storage capacity of a fence	t/m
$\mathbf{Q_c/Q}$	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
$\mathbf{A/A_e}$	Ratio of the pre-equilibrium drift area (**A**), to the area that would be occupied by equilibrium drift ($\mathbf{A_e}$), when fence capacity exceeds transport	none
$\mathbf{S_{we,AS}}$	Water equivalent of snowfall over the drift accumulation season	m
D	Observed setback distance of a snow fence	m
$\mathbf{D_{35}}$	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	$\mathbf{L}/\mathbf{H} = 12 + 49\mathbf{P} + 7\mathbf{P}^2 - 37\mathbf{P}^3$	Tabler (2003)
Equation 2	Pre-equilibrium drift length	$\mathbf{L}/\mathbf{H} = 10.5 + 6.6(\mathbf{A}/\mathbf{A_e}) + 17.2(\mathbf{A}/\mathbf{A_e})^2$	Tabler (2003)
Equation 3	Living snow fence drift length	$\mathbf{L}/\mathbf{H} = ([10.5 + 6.6(\mathbf{A}/\mathbf{A_e}) + 17.2(\mathbf{A}/\mathbf{A_e})^2]/34.3)(12 + 49\mathbf{P} + 7\mathbf{P}^2 - 37\mathbf{P}^3)$	Tabler (2003)
Equation 4	Average annual snow transport	$\mathbf{Q} = 1500(0.17)(\mathbf{S_{we,AS}})(1\text{-}0.14^{\mathbf{F}/3000})$	Tabler (2000)
Equation 5	Snowfall water equivalent over the accumulation season	$\mathbf{S_{we,AS}} = (-695.4 + 0.076{*}\mathbf{Elev} + 17.108{*}\mathbf{Lat})(0.10)$	Tabler (2000)
Equation 6	Snow storage capacity of a fence	$\mathbf{Q_c} = (3 + 4\mathbf{P} + 44\mathbf{P}^2 - 60\mathbf{P}^3)\ \mathbf{H}^{2.2}$	Tabler (2003)
Equation 7	Capacity/Transport ratio of a fence	$\mathbf{Q_c}/\mathbf{Q}$	Current Study
Equation 8	Required height of a fence	$\mathbf{H_{req}} = (\mathbf{Q}/8.5)^{0.455}$	Tabler (2003)
Equation 9	Predicted setback of a living snow fence	$\mathbf{D_{35}} = (\sin\boldsymbol{\alpha})35\mathbf{H_{req}}$	Tabler (2003)
Equation 10	Length of downwind drift model 1	$\mathbf{L} = ([10.5 + 6.6(\mathbf{Q}/\mathbf{Q_c}) + 17.2(\mathbf{Q}/\mathbf{Q_c})^2]/34.3)(12 + 49\mathbf{P} + 7\mathbf{P}^2 - 37\mathbf{P}^3)(\mathbf{H})$	Tabler (2003)
Equation 11	Length of downwind drift model 2	$\mathbf{L} = ([10.5 + 6.6(\mathbf{Q}/\mathbf{Q_c}) + 17.2(\mathbf{Q}/\mathbf{Q_c})^2]/34.3)(12 + 49\mathbf{P} + 7\mathbf{P}^2 - 37\mathbf{P}^3)(\mathbf{H_{req}})$	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

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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 Betters

(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* ($\mathbf{C_r}$). 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 ($\mathbf{C_r}$) is the estimated fraction (expressed as a decimal) of snowfall lifted off the ground and relocated (transported) by the wind. *Storage capacity* ($\mathbf{Q_c}$) 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 ($\mathbf{H_{req}}$) 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 $\mathbf{H_{req}}$ 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, $\mathbf{H_{req}}$ 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 (**D_{35}**). Predicted setback (**D_{35}**) 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 2**Q**, 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 ($\mathbf{H_{req}}$) (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 is 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 ($\mathbf{H_{req}}$), 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 ($\mathbf{Q_c/Q}$) on the right side of each illustration within Figure 1. As living snow fences grow and mature over time, their snow storage capacity ($\mathbf{Q_c}$) often exceeds snow transport ($\mathbf{Q}$), which shortens the length of the downwind drift and the required setback distance.

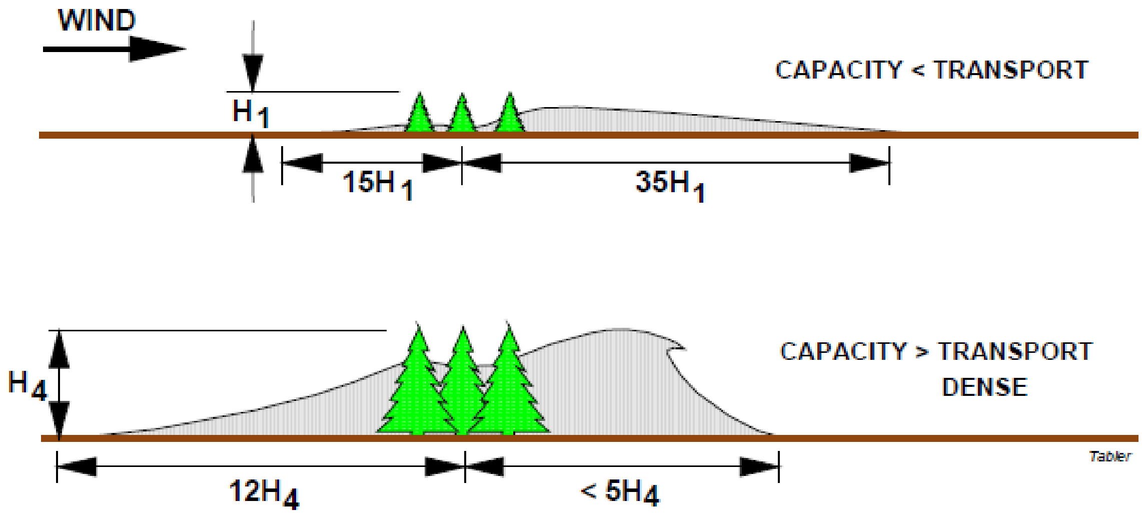

Figure 1: Changes in snowdrift shape and length as a result of changes in fence height, optical porosity, and capacity (**Q_c**) relative to snow transport (**Q**) of living snow fences (Tabler 2003, reproduced with permission)

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 **α**)(35**H_{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 (**D_{35}**) 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.

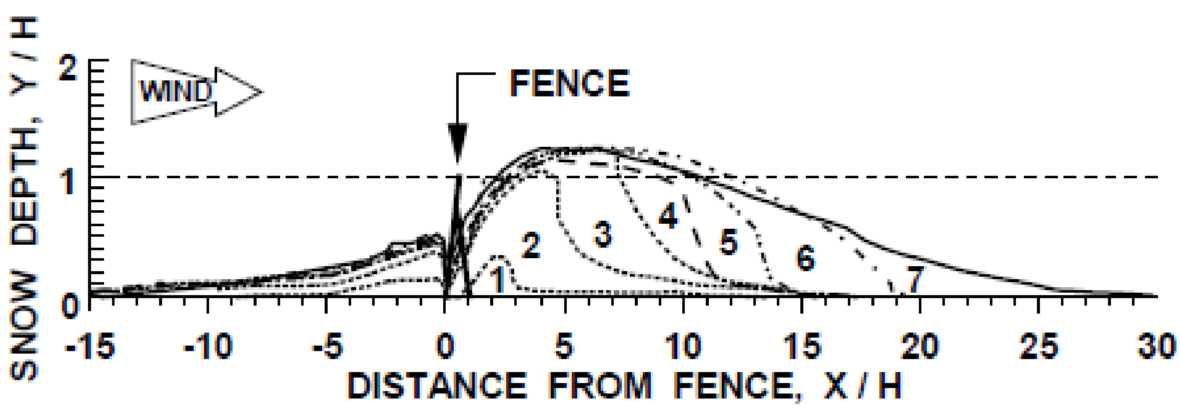

Figure 2: Progressive stages of snow drift formation around a 50% porous barrier (Tabler 2003, reproduced with permission)

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 ($\mathbf{Q_c} >> \mathbf{Q}$), 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 ($\mathbf{Q_c}$>$\mathbf{Q}$), 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 ($\mathbf{Q_c}$>>$\mathbf{Q}$), 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 ($\mathbf{Q_c}$/$\mathbf{Q}$). Dense living snow fences (low porosity) with large capacity/transport ratios ($\mathbf{Q_c}$>>$\mathbf{Q}$) 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 $\mathbf{A/A_e}$ 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 ($\mathbf{A_e}$). 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 $\mathbf{A/A_e}$ is equivalent to the ratio of transport to capacity ($\mathbf{Q/Q_c}$) 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 ($\mathbf{H}$) of the fence, or the required height ($\mathbf{H_{req}}$). 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 35Hreq*". 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 ($\mathbf{H_{req}}$), 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 indentify 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).

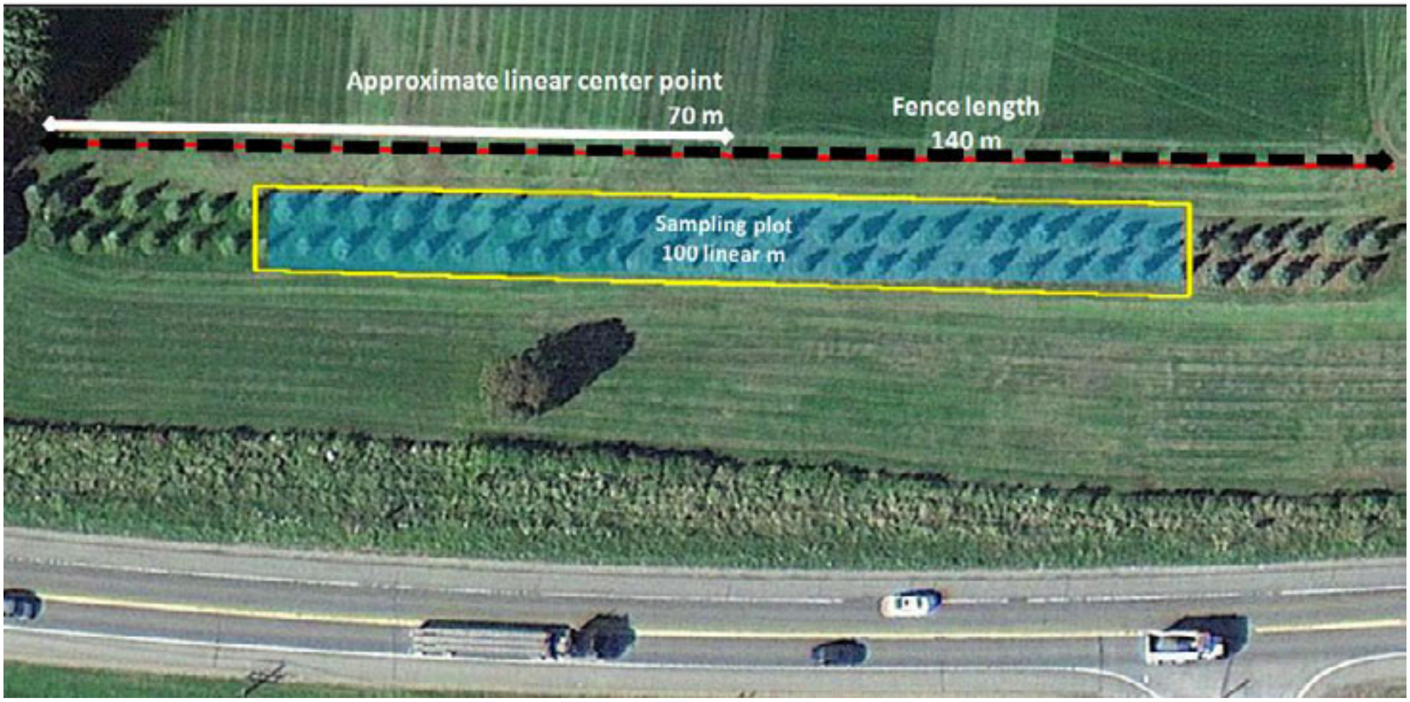

Figure 3: Diagram of fence length and 100 m sampling plot used in this study, established around the approximate linear center of living snow fence Pomfret-conifer-5

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^o 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^o 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.

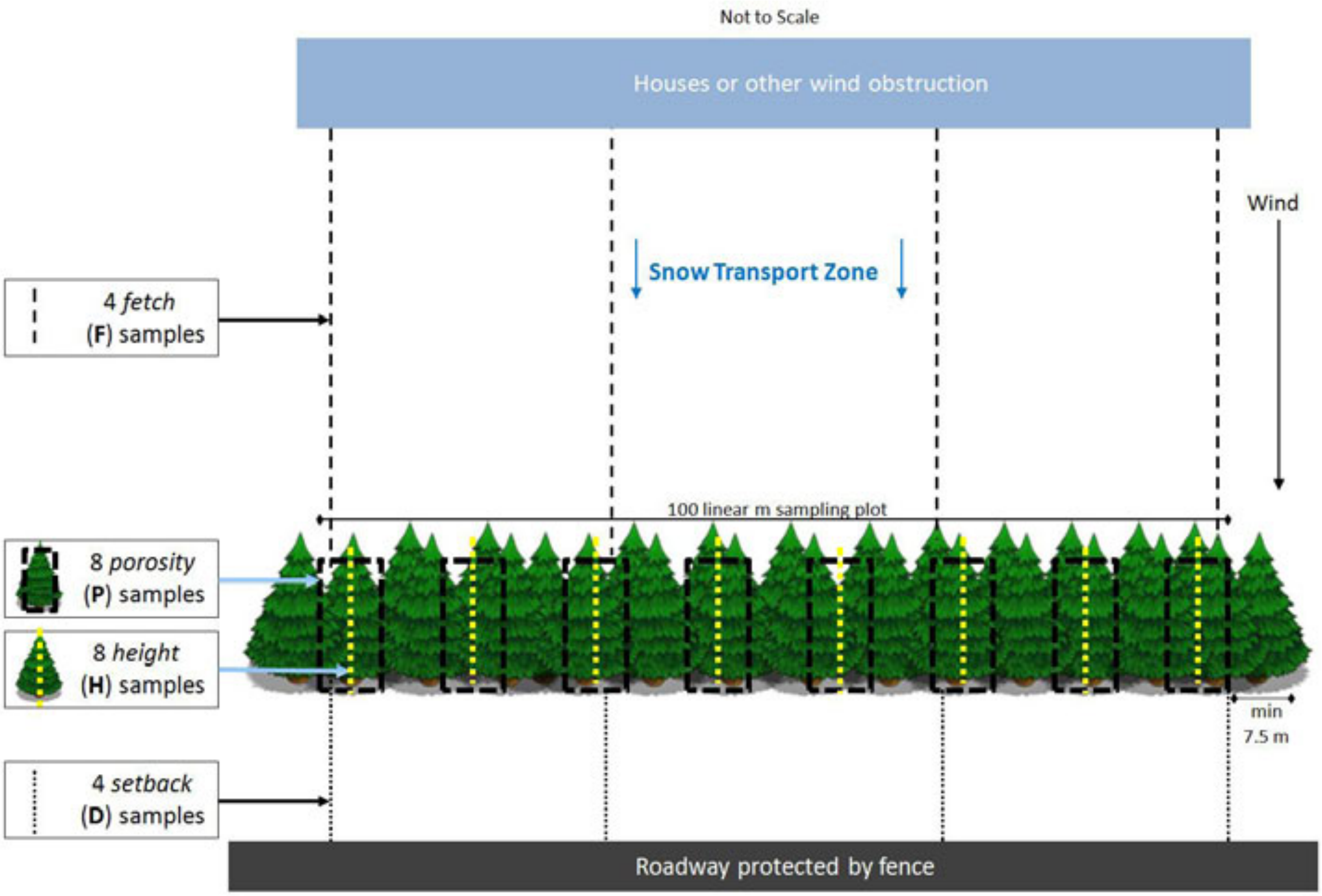

Figure 4: Sampling diagram of remote measurements of site fetch and setback; and field measurements of fence height and optical porosity

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

<u>Average Annual Snow Transport</u> (**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*":

$$\mathbf{Q} = 1500(0.17)(\mathbf{S_{we,AS}})(1\text{-}0.14^{\mathbf{F}/3000})$$

Equation 4

Where:

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

(0.17) is the assumed snow relocation coefficient ($\mathbf{C_r}$)

($\mathbf{S_{we,AS}}$) is the water equivalent of snowfall over the drift accumulation season in meters

F is the fetch distance in meters

The assumed $\mathbf{C_r}$ 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

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 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 is this study was calculated using the observed height and porosity values from each fence and the following model from Tabler (2003):

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

Equation 6

Where:

$\mathbf{Q_c}$ 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 ($\mathbf{Q_c}$) 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).

$$\text{capacity/transport ratio} = \mathbf{Q_c}/\mathbf{Q}$$

Equation 7

Required Height ($\mathbf{H_{req}}$)

The required height ($\mathbf{H_{req}}$) of each snow fence, based on the average annual transport (**Q**) at the fence site, was estimated using the following model from Tabler (2003):

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

Equation 8

Where:

$\mathbf{H_{req}}$ is the required height of the fence in meters

Q is the average annual transport in t/m

Predicted Setback ($\mathbf{D_{35}}$)

The predicted setback ($\mathbf{D_{35}}$) was calculated for each fence in this study using the following model from Tabler (2003):

$$\mathbf{D_{35}} = (\sin\boldsymbol{\alpha})35\mathbf{H_{req}}$$

Equation 9

Where:

$\mathbf{D_{35}}$ is the predicted setback distance in meters

$\boldsymbol{\alpha}$ is the degree of the angle of prevailing winter wind relative to the roadway

$\mathbf{H_{req}}$ is the required height of a 50% porous fence in meters

The angle of the wind to road $\boldsymbol{\alpha}$ was assumed to be 90^o 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^o and 90^o (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):

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

Equation 3

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 ($\mathbf{H_{req}}$) (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:

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

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

$\mathbf{Q_c}$ 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:

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

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

$\mathbf{Q_c}$ is the estimated fence capacity in t/m

P is the observed fence porosity

$\mathbf{H_{req}}$ is the required height of the fence based on the transport quantity (**Q**)

The variables ($\mathbf{Q}/\mathbf{Q_c}$) are again substituted here for ($\mathbf{A}/\mathbf{A_e}$) 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 preformed 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 preformed 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 preformed 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 preformed and the corresponding r^2 values, p values, and S values were in 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 preformed 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 in 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 m ±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.

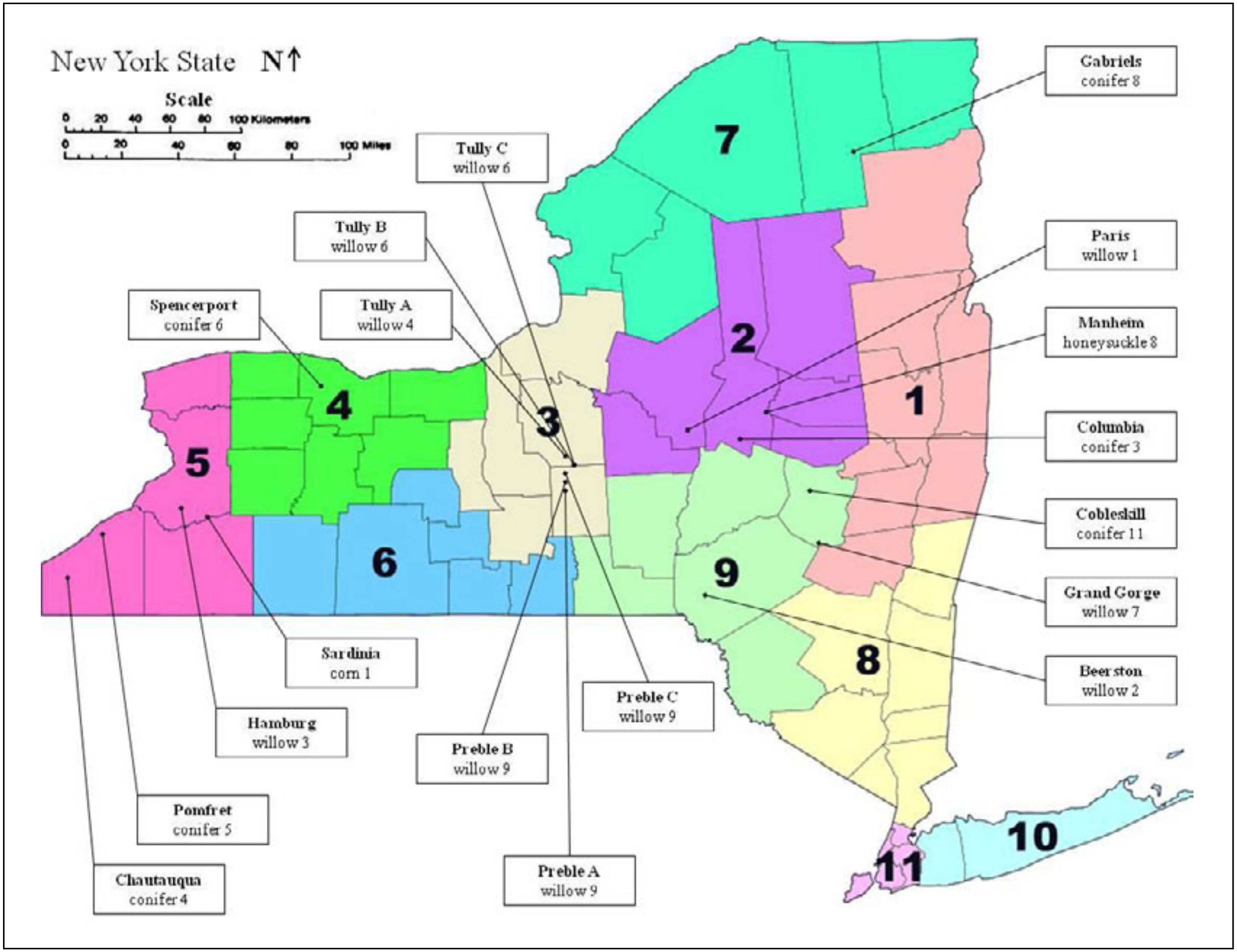

Figure 7: Map of New York State showing NYSDOT regions, approximate locations, and identification tags (town name, vegetation type, age) of the 18 living snow fences investigated in this study

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	*Zea mays*	standing corn rows	350	0.10	8	0.75	340
Manheim - honeysuckle - 8	*Lonicera tatarica*	Arnold red honeysuckle	181	0.91	1	-	206
Paris - willow - 1	*Salix purpurea, Salix miyabeana*	var. SX64, Fishcreek	115	0.61	2	0.76	275
Beerston - willow - 2	*Salix miyabeana, Salix purpurea*	var. SX64, Fishcreek	410	0.61	2	0.76	128
Hamburg - willow - 3	*S. sachalinensis, S. dasyclados*	var. SX61, 98101-61	264	0.61	2	0.76	780
Tully A - willow - 4	*Salix miyabeana, Salix purpurea*	var. SX64, Fishcreek	482	0.61	2	0.76	750
Tully B - willow - 6	*Salix caprea hybrid*	var. S365	235	0.61	2	0.76	185
Tully C - willow - 6	*S. sachalinensis x S. miyabeana*	var. Sherburne	235	0.61	2	0.76	185
Grand Gorge - willow - 7	*Salix purpurea*	shrub-willow purpurea	158	0.31	1	-	171
Preble A - willow - 9	*S. miyabeana, S. sachalinensis*	var. SX64, SX61, 98101-61, 9870-42	192	0.61	2	0.76	480
Preble B - willow - 9	*S. miyabeana, S. sachalinensis*	var. SX64, SX61, 98101-61, 9870-42	115	0.61	2	0.76	370
Preble C - willow - 9	*S. miyabeana, S. sachalinensis*	var. SX64, SX61, 98101-61, 9870-42	116	0.61	2	0.76	538
Columbia - conifer - 3	*Picea abies*	Norway spruce	67	3.05	3	2.13	855
Chautauqua - conifer - 4	*Picea pungens*	blue spruce	185	3.66	3	3.05	620
Pomfret - conifer - 5	*Picea pungens*	blue spruce	140	3.66	2	3.05	437
Spencerport - conifer - 6	*Pseudotsuga menziesii*	Douglas-fir	373	1.83	1	-	157
Gabriels - conifer - 8	*Thuja occidentalis*	northern white cedar	345	2.13	1	-	470
Cobleskill - conifer - 11	*Abies concolour*	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 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: $\mathbf{H_{req}} = (\mathbf{Q}/8.5)^{0.455}$] 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 m ±0.3 m, whereas the mean observed height was 3.8 m ±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 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.

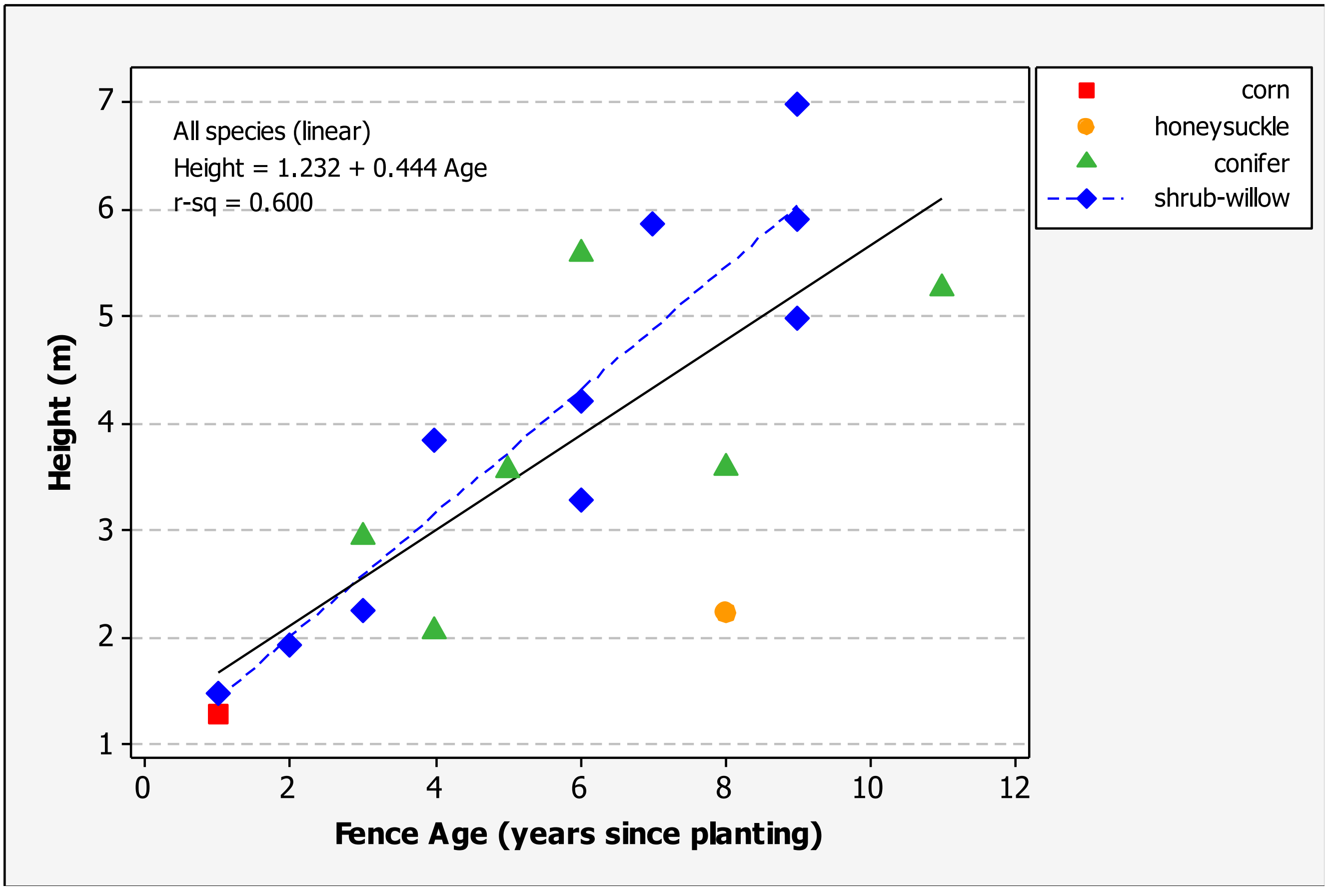

Figure 8: Age (years since planting) versus height (**H**) of 18 living snow fences of various species in New York State, grouped by vegetation type

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	*1.0*	*3.8*	*50%*	*185*	*9*	*27*
Median	*1.0*	*3.6*	*50%*	*167*	*8*	*16*
Standard Deviation	*0.3*	*1.7*	*20%*	*141*	*5*	*31*

Note* - The $\mathbf{Q_c}$ and **Q** values reported in this table were rounded to the nearest t/m for clarity. The capacity/transport ratios ($\mathbf{Q_c}$/**Q**) reported in this table are the rounded ratio of the *actual* capacity and transport values modeled in this study

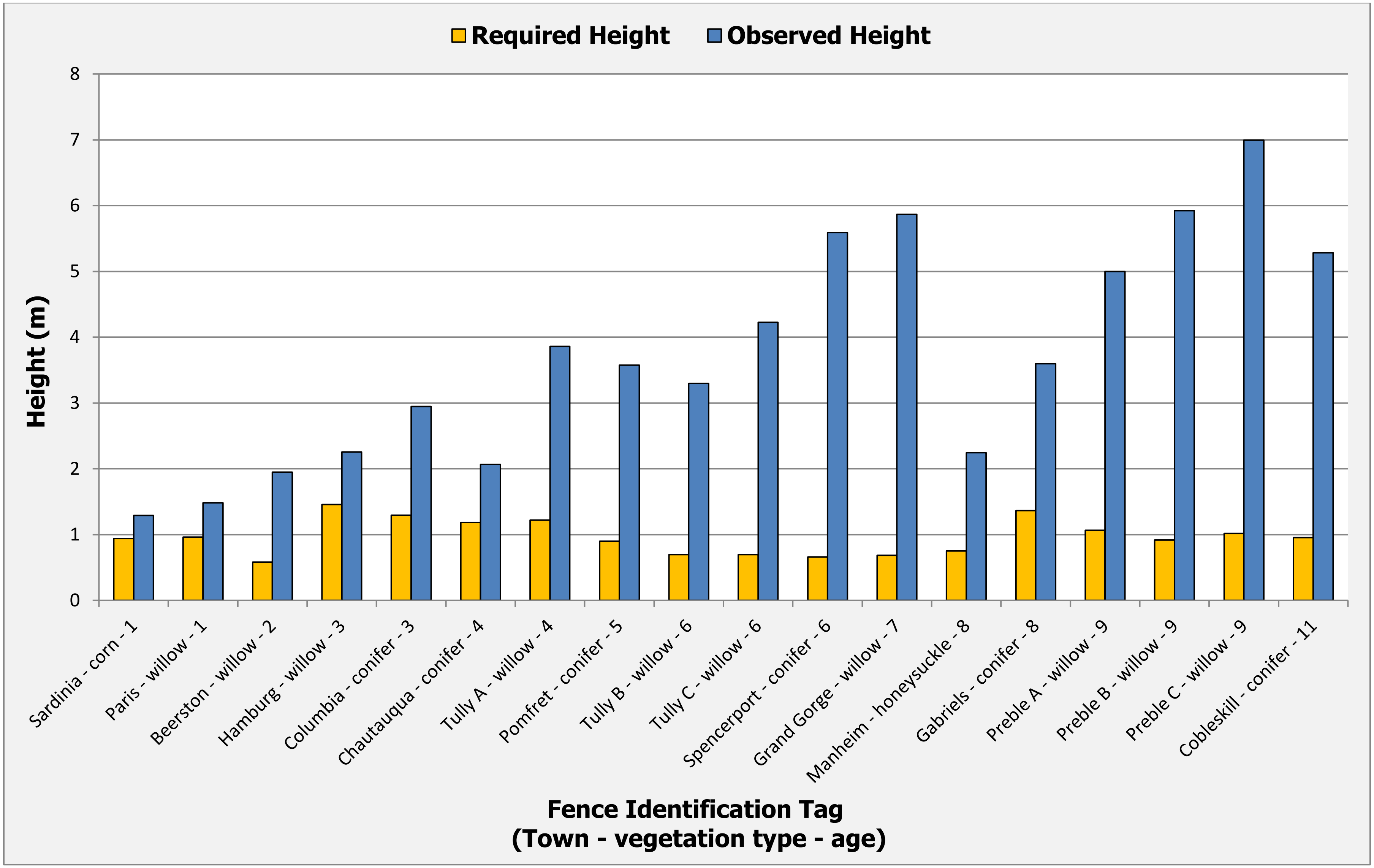

Figure 9: Observed height (**H**) compared to the predicted required height ($\mathbf{H_{req}}$) of 18 living snow fences of various species and ages (years since planting) in New York State

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 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.

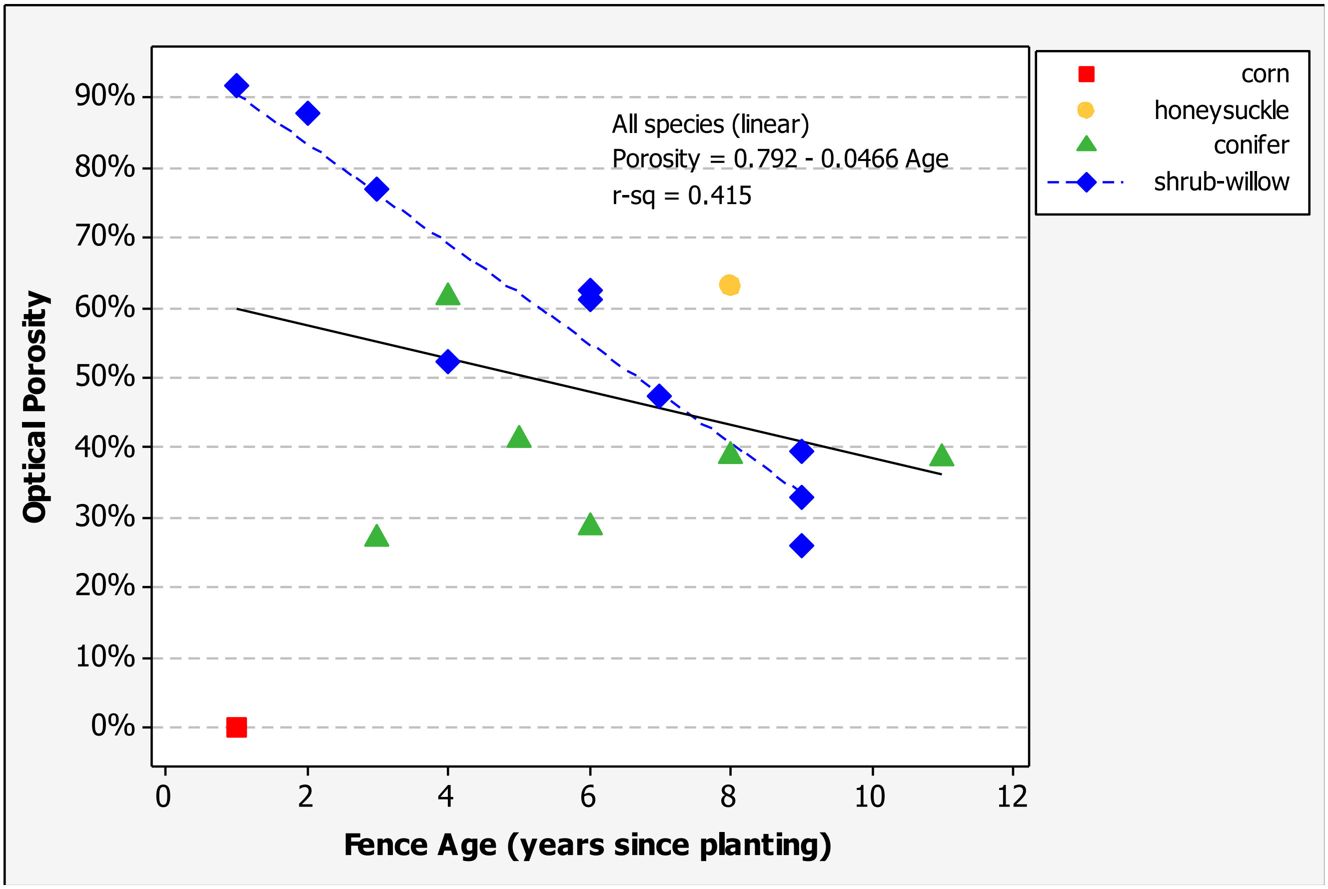

Figure 10: Age (years since planting) versus optical porosity (**P**) of 18 living snow fences of various species in New York State, grouped by vegetation type

4.3 Capacity and Transport

There was a strong positive linear relationship ($p < 0.001$) between age and capacity ($\mathbf{Q_c}$) 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: $\mathbf{Q_c} = (3 + 4\mathbf{P} + 44\mathbf{P}^2 - 60\mathbf{P}^3)\,\mathbf{H}^{2.2}$]. 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, $r^2 = 0.554$, $p = 0.090$).

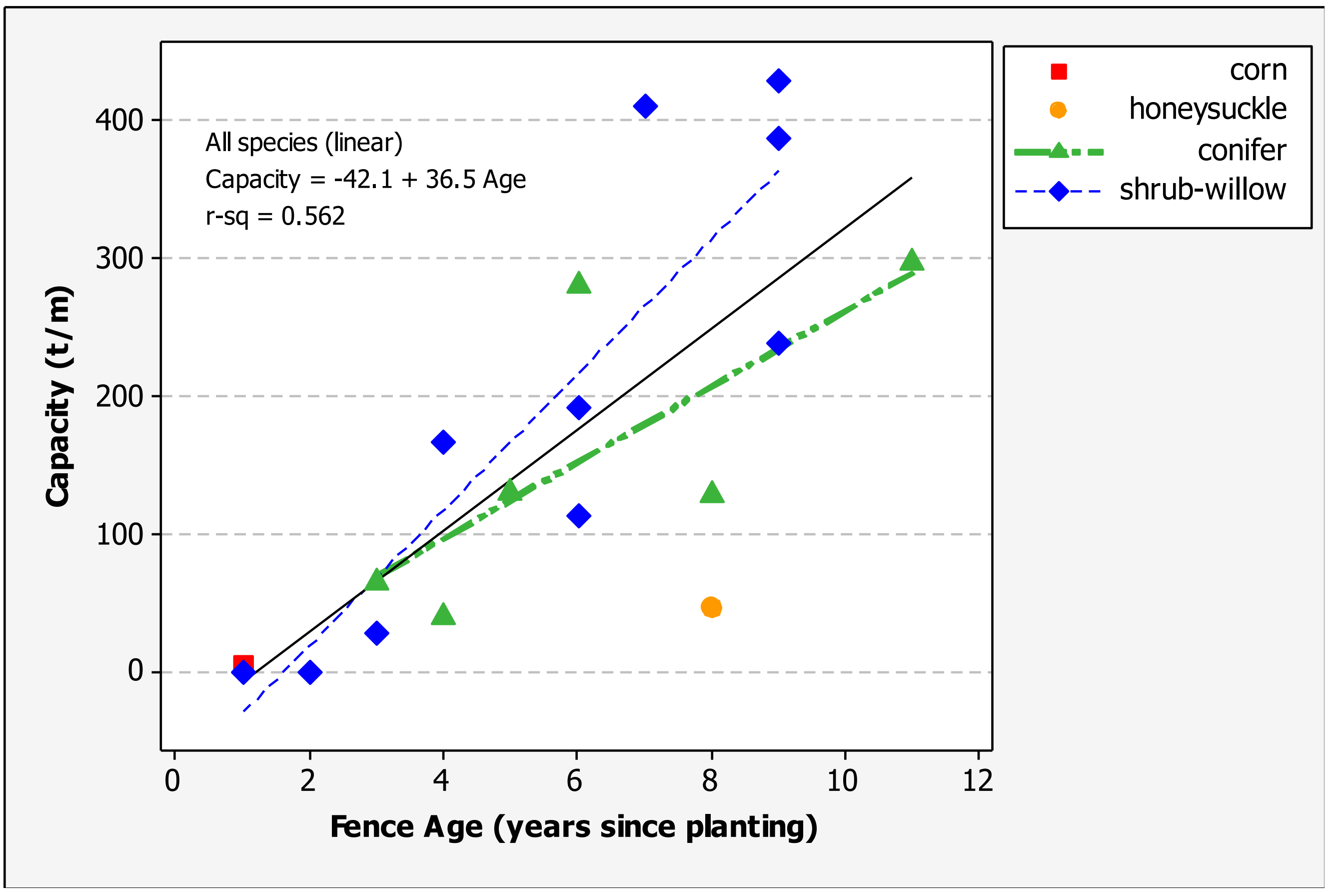

Figure 11: Age (years since planting) versus capacity (Q_c) of 18 living snow fences of various species in New York State, grouped by vegetation type

Snow transport (**Q**) across all sites ranged from 3 - 19 t/m, and the mean was 9 t/m ±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 ($\mathbf{H_{req}}$), 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 ($\mathbf{Q_c \geq Q}$) at early ages.

The capacity/transport ratio ($\mathbf{Q_c/Q}$) 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 $\mathbf{Q_c/Q}$ ratio of Columbia-conifer-3 was 4:1 after three growing seasons. The $\mathbf{Q_c/Q}$ ratio for Tully-A-willow-4 was 13:1, nearly 10 times the $\mathbf{Q_c/Q}$ 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 $\mathbf{Q_c/Q}$ 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 $\mathbf{Q_c/Q}$ ratio was between 8:1 and 110:1, indicating that fences had large amounts of excess storage capacity at early ages. The largest $\mathbf{Q_c/Q}$ 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, Spencerport-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 $\mathbf{Q_c/Q}$ 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 $\mathbf{Q_c/Q}$ ratio.

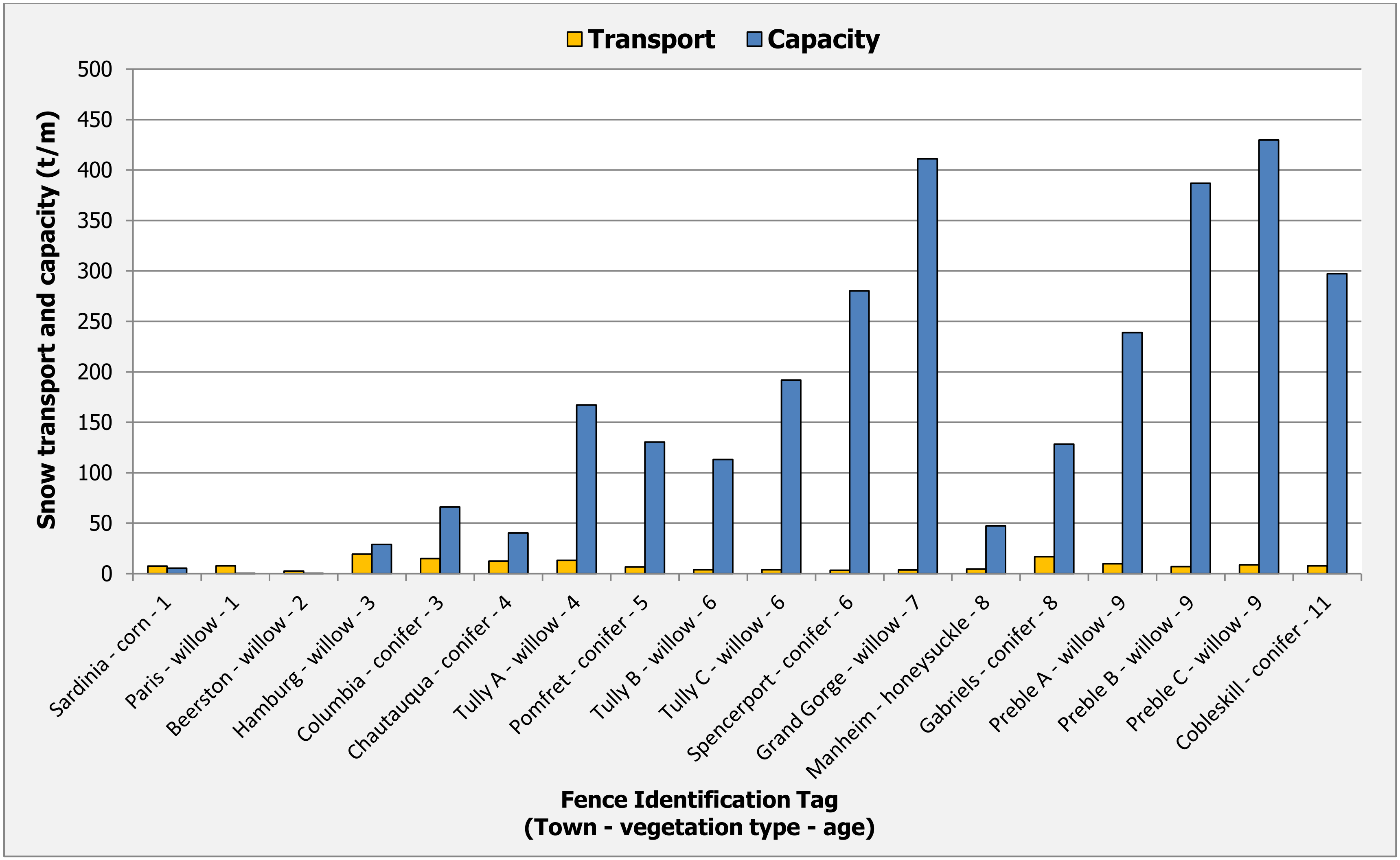

Figure 12: Fence capacity (**Q_c**) relative to the quantity of snow transport (**Q**) at each site for 18 living snow fences of various species and ages (years since planting) in New York State

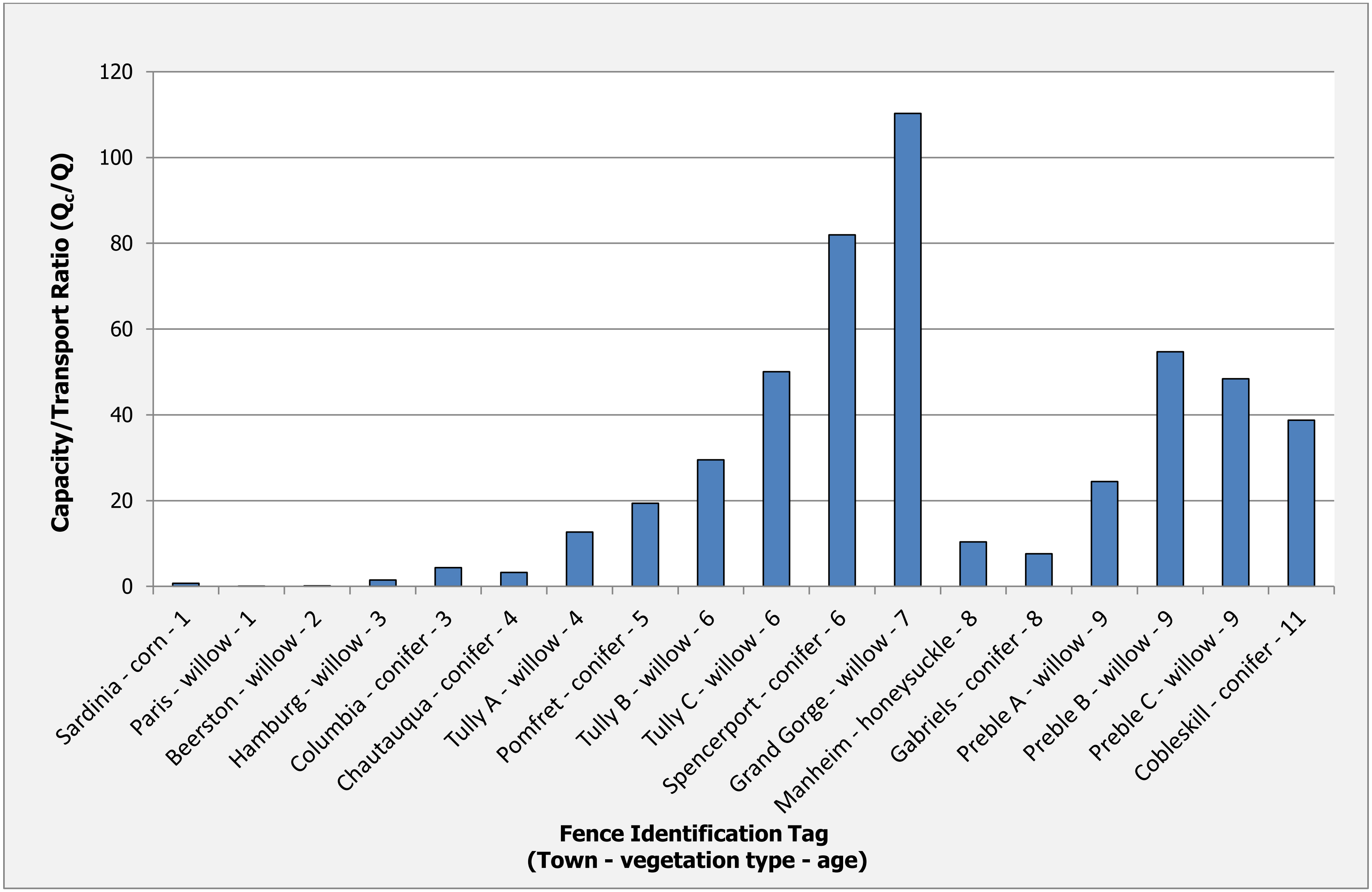

Figure 13: Capacity/Transport ratio (**Q_c/Q**) of 18 living snow fences of various species and ages (years since planting) in New York State

4.4 Setback and Drift Length

There was no significant relationship between observed setback distance (**D**) and the predictor variables of height (**H**), capacity ($\mathbf{Q_c}$), snow transport (**Q**), capacity/transport ratio ($\mathbf{Q_c/Q}$), nor predicted setback ($\mathbf{D_{35}}$) ($p > 0.417$). 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 ($\mathbf{D_{35}}$) was considerably smaller at 18 m - 46 m. The mean of observed setback distances was 34 m ±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 ±8 t/m, compared to the larger standard deviation of observed values of ±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 ±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 ($\mathbf{D_{35}}$) for 14 of 18 fences.

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

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 (**D_{35}**) (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	*34*	*30*	*42*	*13*	*27*
Median	*31*	*30*	*43*	*9*	*16*
Standard Deviation	*24*	*8*	*12*	*8*	*31*

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).

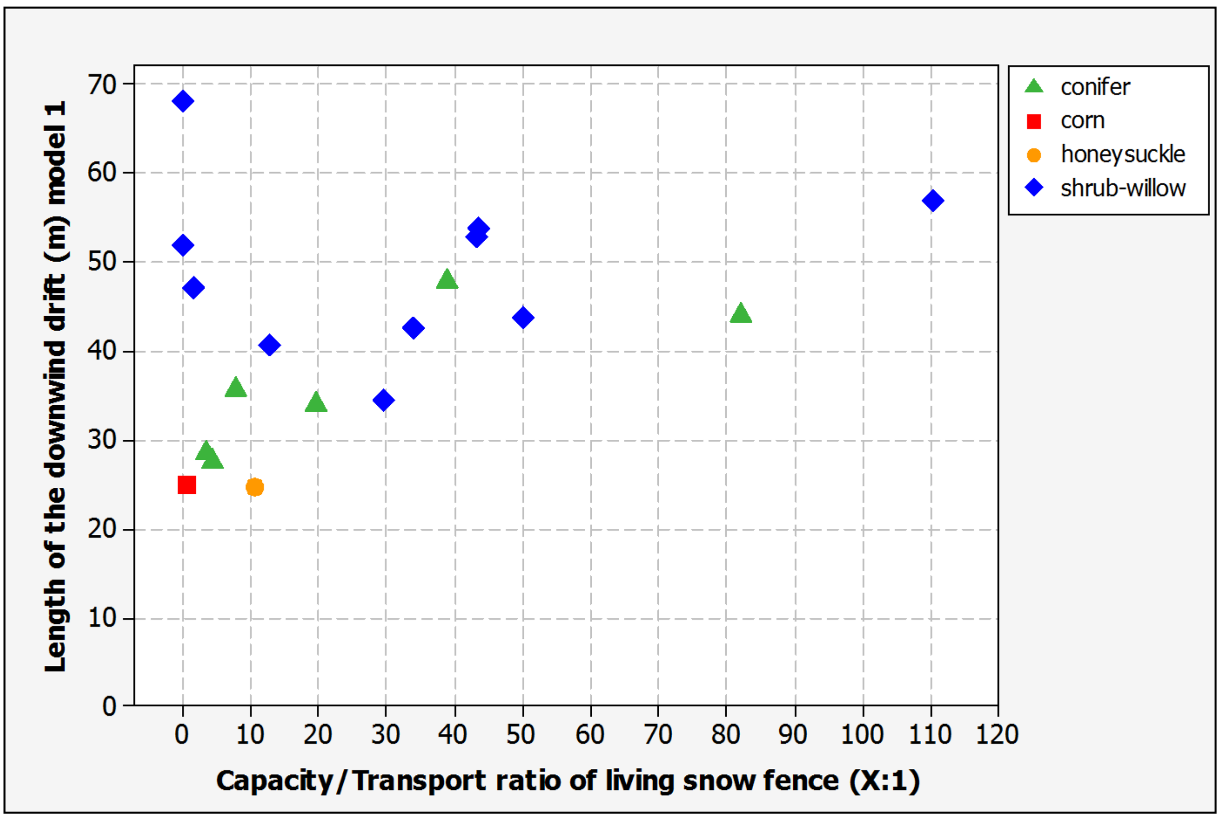

Figure 14: Capacity/Transport ratio versus length of the downwind snow drift as predicted by drift model 1 for 18 living snow fences of various ages (years since planting) and species in New York State

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 ($\mathbf{D_{35}}$) for 16 of 18 fences (Table 4).

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

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 ($\mathbf{Q_c/Q}$) 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

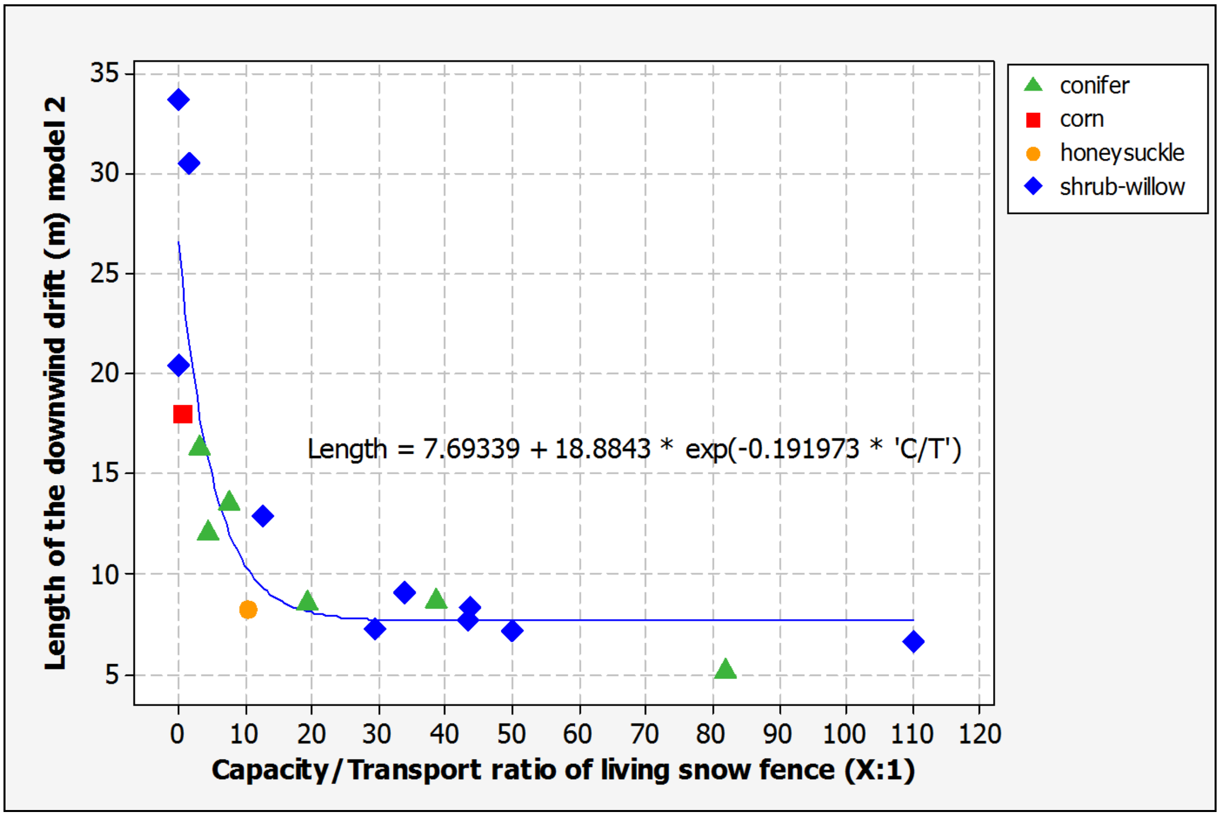

Figure 15: Capacity/Transport ratio (**Q_c/Q**) versus length of the downwind snow drift as predicted by drift model 2 for 18 living snow fences of various ages (years since planting) and species in New York State

Table 5: Summary of regressions, p values, r^2 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 ($\mathbf{Q_c} \geq \mathbf{Q}$), 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 ($\mathbf{Q_c} > \mathbf{Q}$) 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 ($\mathbf{Q_c} \geq \mathbf{Q}$). 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 productions 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, Loefler 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 ($\mathbf{Q_c}>\mathbf{Q}$) 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 ($\mathbf{Q_c}$>$\mathbf{Q}$) 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 ($\mathbf{D_{35}}$). This indicates that there is likely more variation than necessary in the setbacks observed in the field. This variationis 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 ($\mathbf{D_{35}}$) (Table 4), indicating that some setback distances are excessively large since predicted setback ($\mathbf{D_{35}}$) 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 (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 than 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 ($\mathbf{Q_c}$>>$\mathbf{Q}$) 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 ($\mathbf{D_{35}}$) 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 ($\mathbf{D_{35}}$) 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), 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 *canno*t 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 ($\mathbf{D_{35}}$), 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 (**D_{35}**). 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 ($\mathbf{C_r}$) 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 ($\mathbf{C_r}$) of 0.17 provided by Tabler

(2000) for New York differed considerably from other studies conducted in Minnesota ($\mathbf{C_r}$ = 0.35) (Shulski and Seeley 2001), and Siberia ($\mathbf{C_r}$ = 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 $\mathbf{C_r}$ 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 $\mathbf{C_r}$ 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 ($\mathbf{Q_c \geq Q}$), 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^o 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-honeyscukle-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 Naaim-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 ($\mathbf{Q_c}$) of 23 t/m. Exact transport values were not reported, but 20 m^2 of snow was reported in the cross-sectional area downwind drift, which would 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 ($\mathbf{Q_c} > \mathbf{Q}$). 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 ($\mathbf{Q_c}>\mathbf{Q}$), 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.

References

Abrahamson LP, Volk TA, Smart LB, Cameron KB (2010) Shrub willow biomass producers handbook. State University of New York College of Environmental Science and Forestry, Syracuse

Arbor Day Foundation (unkown year) Conservation Trees Fact Sheet: How to create living snow fences. Arbor Day Foundation, Nebraska City http://www.arborday.org/programs/graphics/conservation-trees/living-snow-fences.pdf

Barkley Y (unkown year) UI extension forestry information series II: alternative forest enterprises no. 7: living snow fences. University of Idaho, Moscow.

Blanken PD (2009) Designing a Living Snow Fence for Snow Drift Control. Arctic, Antarctic, and Alpine Research 41:418-425

Brand MH (2013) UConn plant database: of trees, shrubs, and vines. University of Connecticut http://www.hort.uconn.edu/plants/

Bratton TL (2006) Living snow fences in Kansas. L-744 Kansas Forest Service, Manhatten http://www.ksre.ksu.edu/bookstore/pubs/L744.PDF

Cameron KD, Loeb GM, Abrahamson LP, White C, and Smart LB (2010) Willowpedia Facts Sheets. Cornell University College of Agriculture and Life Sciences, Geneva

Colorado State University Extension (2013) Small acreage management: windbreaks and living snow fences. Colorado State University Extension, Fort Collins http://www.ext.colostate.edu/sam/windbreaks.html

Cornell Cooperative Extension (2011) Home grown facts: living snow fences. Cornell Cooperative Extension, Oneida County

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

Goodwin LC (2003) Best practices for road weather management. Mitretek Systems Inc, Falls Church

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

Hardin JW, Leopold DJ, and White FM (2001) Textbook of dendrology: ninth edition. McGraw Hill, Boston

Heavey JP and Volk TA (2013a) Cost-Benefit Model for Living Snow Fences in New York State. State University of New York College of Environmental Science and Forestry, Syracuse

Heavey JP and Volk TA (2013b) Living Snow Fence Fact Sheet Series. State University of New York College of Environmental Science and Forestry, Syracuse

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

Josiah S and Majeski M (2002) Living snow fences. University of Minnesota, Minneapolis

Kenaley SC, Hudler GW, O'Brien DD, Cameron KD, Smart LB (2011) Willowpedia Facts Sheets. Cornell University College of Agriculture and Life Sciences, Geneva

Kenney WA (1985) The effect of inter-tree spacing on the porosity of shelterbelts and windbreaks. M.Sc. Thesis, University of Guelph, Guelph, Ontario, pp 58

Komarov AA (1954) Some rules on the migration and deposition of snow in western Siberia and their application to control measures. National Research Council of Canada Technical Translation Ottawa 4: 89-97

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

Kuzovkina YA and Quigley MF (2005) Willows beyond wetlands: uses of *Salix* species for environmental projects. Water, Air, and Soil Poll 162: 83-204

Lashmet (2013) Snow and ice control in New York State. Presentation from Lake George Park Commission Forum, April, 2013. New York State Department of Transportation, Office of Transportation Maintenance, Albany

Loefler AE, Gordon AM, and Gilespie TJ (1992) Optical porosity and windspeed reduction coniferous windbreaks in Southern Ontario. Agroforest Syst 17:119-133

Naaim-Bouvet F and Mullenback P (1998) Field experiments on "living" snow fences. Annals of Galciology, 26:217-220

NCHRP National Cooperative Highway Research Program (2005) NCHRP Synthesis 344 Winter Highway Operations. Transportation Research Board, Washington D.C.

NRCS Natural Resources Conservation Service (2012) Working Trees Fact Sheet Series. Natural Resources Conservation Service, USDA National Agroforestry Center, Lincoln

NRCS Natural Resources Conservation Service (2007) Documentation of eligibility and suitability for living snow fences CP17A. Natural Resources Conservation Service, USDA National Agroforestry Center, Lincoln

NYSDOT New York State Department of Transportation (2012) Living snow fences: design basics. New York State Department of Transportation, Albany

NYSDOT New York State Department of Transportation (2011) Existing Living Snow Fence Locations. New York State Department of Transportation, Albany

NYSDOT New York State Department of Transportation (2010a) Average accident costs/severity distribution state highways 2010. New York State Department of Transportation, Safety Information Management System, Albany

NYSDOT New York State Department of Transportation (2010b) GreenLITES Project Design Certification Program: Recognizing Leadership in Transportation and Environmental Sustainability. New York State Department of Transportation, Albany

Peterson T and Schmidt R (1984). Outdoor scale modeling of shrub barriers in drifting snow. Agric. For. Meteorol 31:167-181

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

Royle DJ, Ostry ME (1995). Disease and pest control in the bioenergy crops poplar and willow. Biomass and Bioenergy 9:69-79

Shaw DL (1988) The design and use of living snow fences in North America. Ag, Ecoyst, and Env 22/23: 351-362

Shaw DL (1989) Living snow fences: Protection that just keeps growing. Colorado Interagency Living Snow Fence Program, Colorado State University, Fort Collins

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 http://www.climate.umn.edu/snow_fence/intro.html

Smart LB and Cameron KD (2008) Genetic improvement of willow (*salix* spp.) as a dedicated bioenergy crop. In Vermerris, W. E. (ed.) Genetic Improvement of Bioenergy Crops: 347-376. Springer Science, New York

South Dakota Department of Agriculture (2004) The living snow fence program in South Dakota. South Dakota Department of Ag, Prince

Streed E and Walton J (2001) Producing marketable products from living snow fences. University of Minnesota Extension, St. Paul

Sturges D (1984) The geometry of snowdrifts cast by shelterbelts as determined by small-scale, outdoor modeling. Rocky Mountain Forest and Range Experiment Station, Laramie

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

Tabler RD (2000) Climatalogic analysis for snow mitigation in New York State: final report. Tabler and Associates, Niwot

Tabler RD (1997) Recommended drift control measures for selected sites in Minnesota. Tabler and Associates, Niwot

Tabler RD (1994) Design guidelines for the control of blowing and drifting snow. Strategic Highway Research Program, Report SHRP-H-381

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

USDA United State Department of Agriculture (2013) USDA PLANTS database. http://plants.usda.gov

USDA United State Department of Agriculture (2012) Conservation Reserve Program Statistics, June 2012. Farm Service Agency (FSA) Statistics. http://www.fsa.usda.gov/Internet/FSA_File/juneonepager2012.pdf

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

USDA United State Department of Agriculture (2006) Conservation Reserve Program Continuous Sign-up. USDA Farm Service Agency, Washington D.C.

USDOT United States Department of Transportation (2003) Revised Departmental Guidance: Valuation of Travel Time in Economic Analysis. U.S. Department of Transportation, Office of the Secretary of Transportation, Washington D.C.

Volk TA, Abrahamson LP, Nowak CA, Smart LB, Tharakan PJ, and White EH (2006) The development of short-rotation willow in the northeastern United States for bionergy and biproducts, agroforestry and phytoremediation. Biomass and Bioenergy 30:715:727

Walvatne PGA (1991) A report on MN/DOT's living snow fence efforts. Minnesota Department of Transportation, Environmental Services Section, St. Paul

Wyatt (2012) Economic and environmental costs and benefits of living snow fences: Safety, mobility, & transportation authority benefits, farmer costs, & carbon impacts. Minnesota Department of Transportation Research Services, Final Report 2012-03

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	*Zea mays*	standing corn rows	1148	4"	8	2' 6"	1115
Manheim - honeysuckle - 8	*Lonicera tatarica*	Arnold red honeysuckle	594	3'	1	-	676
Paris - willow - 1	*Salix purpurea, Salix miyabeana*	var. SX64, Fishcreek	377	2'	2	2' 6"	902
Beerston - willow - 2	*Salix miyabeana, Salix purpurea*	var. SX64, Fishcreek	1345	2'	2	2' 6"	420
Hamburg - willow - 3	*S. sachalinensis, S. dasyclados*	var. SX61, 98101-61	866	2'	2	2' 6"	2559
Tully A - willow - 4	*Salix miyabeana, Salix purpurea*	var. SX64, Fishcreek	1581	2'	2	2' 6"	2461
Tully B - willow - 6	*Salix caprea hybrid*	var. S365	771	2'	2	2' 6"	607
Tully C - willow - 6	*S. sachalinensis x S. miyabeana*	var. Sherburne	771	2'	2	2' 6"	607
Grand Gorge - willow - 7	*Salix purpurea*	shrub-willow purpurea	518	1'	1	-	561
Preble A - willow - 9	*S. miyabeana, S. sachalinensis*	var. SX64, SX61, 98101-61, 9870-42	630	2'	2	2' 6"	1575
Preble B - willow - 9	*S. miyabeana, S. sachalinensis*	var. SX64, SX61, 98101-61, 9870-42	377	2'	2	2' 6"	1214
Preble C - willow - 9	*S. miyabeana, S. sachalinensis*	var. SX64, SX61, 98101-61, 9870-42	381	2'	2	2' 6"	1765
Columbia - conifer - 3	*Picea abies*	Norway spruce	220	10'	3	7'	2805
Chautauqua - conifer - 4	*Picea pungens*	blue spruce	607	12'	3	10'	2034
Pomfret - conifer - 5	*Picea pungens*	blue spruce	459	12'	2	10'	1434
Spencerport - conifer - 6	*Pseudotsuga menziesii*	Douglas-fir	1224	6'	1	-	515
Gabriels - conifer - 8	*Thuja occidentalis*	northern white cedar	1132	7'	1	-	1542
Cobleskill - conifer - 11	*Abies concolour*	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 $\mathbf{Q_c}$ 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 ($\mathbf{Q_c/Q}$) 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	*112*	*98*	*138*	*43*	*27*
Median	*102*	*98*	*141*	*30*	*16*
Standard Deviation	*79*	*26*	*39*	*26*	*31*

Appendix 2 – Photos of Living Snow Fences

Figure 16: Living snow fence Sardinia-corn-1from 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

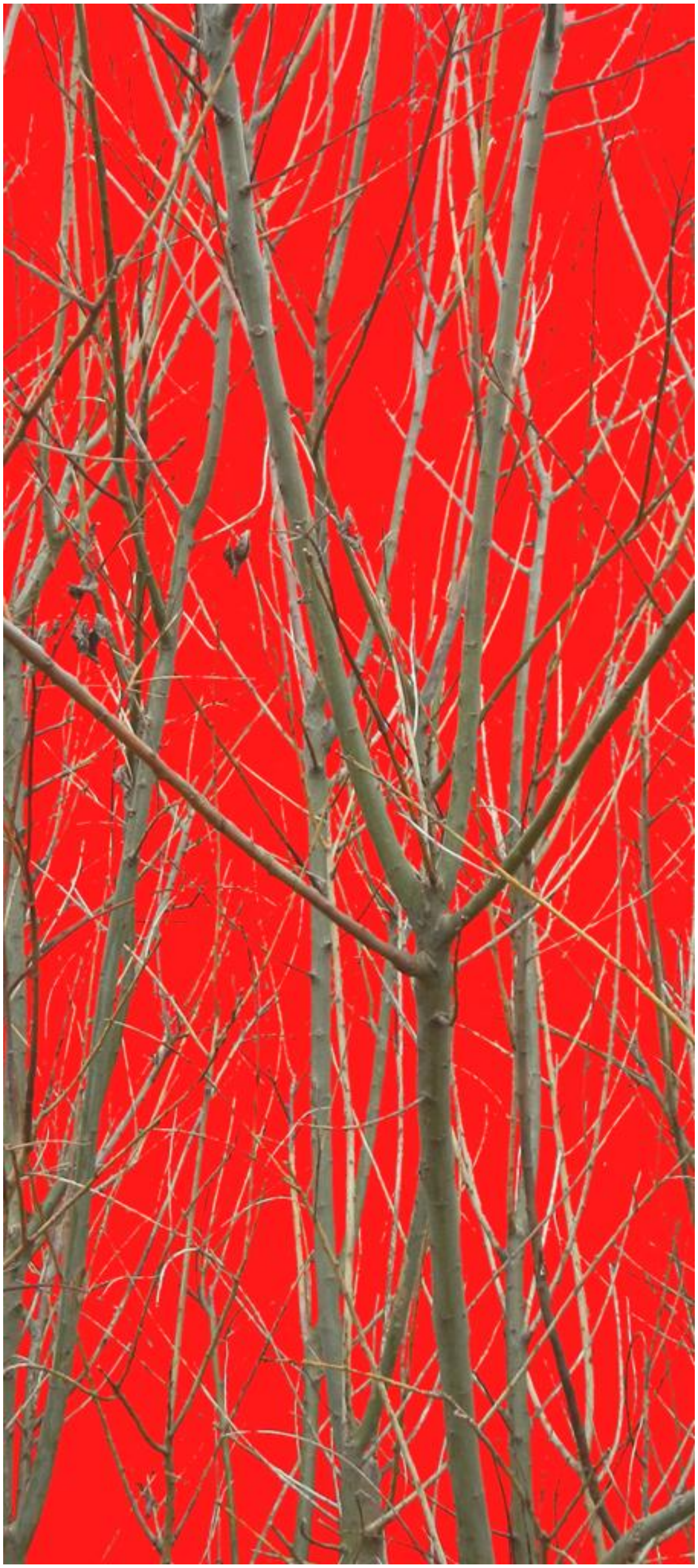

Figure 32: Optical porosity photo sample from living snow fence Tully-B-willow-6 showing stem morphology of shrub-willow variety S365

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 angel 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

Resume for Justin P. Heavey

Qualifications in Sustainability and Natural Resource Management

Knowledgeable and experienced in sustainability management and the most pertinent environmental disciplines
High aptitude for quantitative analysis complimented by exceptional communication skills
Demonstrated ability to successfully initiate, manage, and finalize complex sustainability projects in large institutions
Accomplished in leading interdisciplinary endeavors in sustainability and facilitating collaboration between stakeholders

Education

State University of New York - College of Environmental Science and Forestry (SUNY-ESF) Syracuse, NY

Master's of Science - Forest and Natural Resource Management 2013
Focus in Management | GPA: 3.73

Bachelor's of Science - Environmental Studies 2011
Focus in Environmental Policy, Planning, & Law | Minor in Renewable Energy Systems | GPA: 3.72

Research and Professional Experience

State University of New York - College of Environmental Science and Forestry (SUNY-ESF) Syracuse, NY

Research Project Assistant - Department of Forest and Natural Resource Management 2011 - 2013
"Designing, Developing, and Implementing a Living Snow Fence Program for New York State"
"Eco-luminance: combined vegetation and energy efficient lighting for safe roadways"

Research Assistant - Office of Renewable Energy Systems 2009 - 2011
"Sustainability Planning and Student Engagement at SUNY-ESF"
"Edible Forest Garden at SUNY-ESF"

Energy Analyst - Office of Renewable Energy Systems 2008 - 2009
"ESF Carbon Neutral by 2015: Climate Action Plan for SUNY-ESF"
"Sustainability Tracking, Assessment, and Ratings System (STARS) Audit for SUNY-ESF"

Service and Community Involvement

Campus Climate Change Committee (Advisory Board) | Committee Member 2009 - 2013
Green Campus Initiative (Student Organization) | Member, Garden Chair, and Compost Chair 2009 - 2013
Environmental Studies Student Organization (Student Outreach) | Founding Member 2009 - 2011

Instruction and Public Speaking

Instructional Assistant - SUNY-ESF & New York State Department of Transportation bi-annual trainings 2011 - 2013
Teaching Assistant - Biophysical Economics (EFB 522) SUNY-ESF 2010
Conference Presenter - Association for the Advancement of Sustainability in Higher Education (AASHE) 2010
Presenter - Undergraduates Shaping New York's Future: A Showcase of Scholarly Posters at the Capitol 2010

Selected Coursework

Introduction to Environmental Studies · Writing for Environmental Professionals · Social Process & the Environment
Government & the Environment · Natural Resource Administration · Concepts & Principles of Sustainable Development
Ecology Resources & Development · Principles of Management · Environmental & Energy Auditing · Renewable Energy
Energy Markets & Regulation · General Ecology · Ecosystems · Restoration Ecology · Soils Plants & Stormwater

Research Interests

Best practices in campus and institutional sustainability · Plant/human interactions in sustainable urban environments
Role of plants and trees in sustainability planning and practice · Sustainable urban forestry, agriculture, and gardens
Landscape eco-mimicry of native plant communities · Restoration and design of sustainable urban and rural ecosystems