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Living snow fences show potential for large storage capacity and reduced drift length shortly after planting

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Abstract

Living snow fences are windbreaks designed to mitigate blowing snow problems by trapping snow in drifts before it reaches a road. Research studies on living snow fences are limited and extension publications consequently lack precise design protocols. This study investigated 18 sites in New York State planted with living snow fences of various vegetation types and ages ranging from one to eleven years after planting. Key plant growth variables of fence height and optical porosity were measured along with distance upwind and downwind. This data was combined with site specific snowfall estimates and established equations to calculate the snow storage capacity of each fence, average annual snow transport (blowing snow) at each site, and length of the downwind drift. Capacity/transport ratio of each fence/site was identified as a key variable. Height increased linearly over time and porosity decreased. Three years after planting, height and porosity was sufficient so that capacity/transport ratios were greater than 1:1, indicating substantial snow trapping potential much sooner than commonly reported. Four to eleven years after planting, capacity/transport ratios were between 3:1 and 110:1. Capacity/transport ratios of 15:1 or greater occurred as early as five years after planting and were correlated with estimated drift lengths less than 10 m. The influence of capacity/transport ratio on drift length is not accounted for in current publications and setback recommendations range from 30 - 180 m. The results of this study can improve the understanding, design and function of living snow fences.

Key Words: windbreaks, shelterbelts, trees, shrub willow, *Salix*, transportation

1. Introduction

Living snow fences (LSF) are an agroforestry practice similar to windbreaks (USDA 2011) that uses rows of trees or shrubs to trap blowing snow in drifts before it reaches a road. Blowing snow problems occur around agricultural fields or other large open areas when fallen snow is lifted off the ground and transported by the wind toward a road, a common problem in cold weather regions around the world. This can lead to snow and ice accumulations on the road, reduced visibility, travel delays, automobile accidents and increased road maintenance costs. LSF disrupt wind patterns causing controlled snow deposition in designated areas. Like other agroforestry systems, LSF combine trees and shrubs with agricultural systems, creating numerous economic, social and environmental benefits.

LSF are considered a best practice by transportation agencies (Goodwin 2003; Lashmet 2013) that can reduce the cost of mechanical and chemical snow controls such as plowing and salting (Tabler 2003). Local and state agencies in the United States alone spend over $2.3 billion annually (2013 US$) on snow control and nearly $6 billion annually to repair transportation infrastructure damaged by snow/ice and associated control practices (NCHRP 2005). LSF perform the same snow trapping function as structural (wooden or plastic) snow fences and can have better cost benefit ratios and positive net present values (Daigneault and Betters 2000). LSF can have useful life cycles that exceed structural snow fences by four to seven times (USDA 2011), or 25 years or more (Powell et al. 1992). Many benefits of LSF have both economic and social impacts. In addition to invaluable human life and wellbeing, the average financial cost (2013 US$) associated with one fatal car accident in New York State is approximately $3.5 million, and $93,000 for injury inducing accidents (NYSDOT 2010). Tabler and Meena (2006) reported a 75% reduction in accident rates in areas protected by snow fences. By improving driving conditions and reducing delays and road closures, LSF provide additional benefits in the value of travel time savings (VTTS), a critical factor in the valuation of transportation projects (USDOT 2003). LSF can also provide a variety of environmental and aesthetic benefits (NRCS 2012; Wyatt 2013) as well as value-added agroforestry crops (Streed and Walton 2001).

Despite the potential for multiple benefits, LSF are biological systems that change over time and have not been extensively researched. Suitable site conditions and best practices are required for optimal growth and snow trapping (Gullickson et al. 1999; Tabler 2003; Heavey and Volk 2013). Utilities, land ownership patterns and other landscape elements can limit the feasibility of LSF on many sites. A number of years (growing seasons) after planting is required before snow trapping begins and this can be delayed several years or indefinitely if best practices are not employed. Once established, LSF are susceptible to environmental stressors and disturbances such as pests and drought. Changing plant characteristics and corresponding snow trapping function complicates design decisions, and there is some uncertainty and hesitation around the use of LSF by transportation officials and resource managers. Extension publications lack quantitative protocols and consensus on important design issues such as setback, or the chosen distance between the fence and the roadway.

The objective of this study was to measure key plant growth and site variables for LSF of various vegetation types and years after planting. This data was combined with models developed by Tabler (2000; 2003) to estimate the snow trapping potential of LSF over time including the of number years between planting and snow trapping, snow storage capacity, downwind drift length and required setback distance. Data results and model estimates are discussed in the context of current publications.

2. Materials and Methods

A stratified sample of LSF was selected based on the ability to identify and access sites in the field, and to represent a range of vegetation types and years after planting (**YAP**). Sites were identified using a list of statewide LSF plantings (NYSDOT 2011), geographic information systems (GIS) and site visits. Sites with distinctly low survival rates or stunted growth were excluded in order to evaluate LSF that best represent the dynamics of plant growth and snow trapping potential over time. Once identified, fences were categorized into four general vegetation types and assigned an identification (ID) tag using the name of the town the fence was located in, a letter for towns with more than one fence/site, the vegetation type, and **YAP** (i.e. Preble-A-willow-9).

The snow trapping variables and terminology used in this study are based on Tabler (2000; 2003) as follows. Height (**H**) is the vertical distance from the ground to the top of the fence vegetation. Optical porosity (**P**) is the percentage of open space when a fence is viewed at a perpendicular angle in winter. Snow storage capacity ($\mathbf{Q_c}$) is the estimated quantity of blowing snow that a fence can store per linear meter in units of metric tons of water equivalent per meter (t/m). $\mathbf{Q_c}$ is primarily a function of **H** and **P** but can be modified by topography and other factors (Tabler 2003). Snow transport (**Q**) is the estimated average annual quantity of blowing snow transported by the wind towards the road in units of t/m. **Q** is a function of fetch distance (**F**), relocation coefficient ($\mathbf{C_r}$), and snowfall water equivalent over the drift accumulation season ($\mathbf{S_{we,AS}}$). **F** is the distance in meters from the fence to the first obstruction upwind (such as a building or forest) assumed to disrupt wind patterns and cause snow deposition. $\mathbf{C_r}$ is the estimated fraction of snowfall lifted off the ground and relocated by the wind. $\mathbf{S_{we,AS}}$ is the estimated snowfall over the period of sustained annual drift growth, delimited by snow that falls before sustained growth or after permanent melt.

Capacity/transport ratio ($\mathbf{Q_c/Q}$) influences the length of the downwind snow drift that extends from the fence toward the road (Tabler 2003; Heavey 2013). If $\mathbf{Q_c/Q}$ is less than or equal to 1:1, maximum downwind drift length is 35H, or 35 times the height of the fence (Tabler 2003), referred to as the equilibrium drift. If $\mathbf{Q_c/Q}$ is *greater* 1:1, drift length is reduced to some fraction of 35H, making $\mathbf{Q_c/Q}$ an important variable in the analysis and design of LSF. Setback (**D**) is the distance between the fence and the road selected during the design phase. The estimated length of the downwind drift (**L**) is a function of **H**, **P**, and $\mathbf{Q_c/Q}$.

To measure fence and site characteristics, a 100 m sampling plot was established around the linear center point of each fence and a series of eight **H** and **P** measurements, and four **D** and **F** measurements were taken within the plot at equidistant spacing. **D** and **F** were measured remotely using GIS. **D** was measured at a perpendicular angle from the fence to the roadway. **F** was measured at a perpendicular angle from the fence to the first obstacle upwind. **H** was measured using a telescoping measuring pole. Two techniques of measuring **P** were used; a chroma-key technique for corn, honeysuckle and shrub willow LSF; and a high contrast photography technique for conifer LSF. The chroma-key technique consisted of a 1 m wide by 3 m tall backdrop of red synthetic fabric held directly behind the fence to accentuate **P** and maximize the accuracy of photographic samples. Eight photographs were taken within the sampling plot of each fence at approximately the same points where height measurements were taken. The chroma-key technique was not viable for conifer LSF due to differences in morphology of this vegetation type (larger and denser trees). The high-contrast photography methods of Loefler et al. (1992) were therefore adapted for conifer LSF to produce equivalent photographic samples in which a strong contrast between open (porous) space and vegetation was created (Fig. 1) allowing the percent **P** to be accurately calculated using standard photo editing software. The series of measurements for each variable was averaged for the reported **H**, **P**, **D**, and **F**, representing the mean values for each unique snow fence/site.

Fig. 1 Examples of processed photos used to measure optical porosity ($\mathbf{P}$) from the chroma-key technique (left, Tully-B-willow-6) and high contrast technique (right, Cobleskill-conifer-11)

Mean $\mathbf{H}$, $\mathbf{P}$ and $\mathbf{F}$ values from each fence/site were modeled using the equations of Tabler (2000; 2003) to estimate $\mathbf{Q_c}$, $\mathbf{Q}$, and $\mathbf{L}$. $\mathbf{Q_c}$ was estimated using the model from Tabler (2003): $\mathbf{Q_c} = (3 + 4\mathbf{P} + 44\mathbf{P}^2 - 60\mathbf{P}^3)\ \mathbf{H}^{2.2}$. Slope was negligible at most sites and no modifications for topography were made to $\mathbf{Q_c}$. $\mathbf{Q}$ was estimated using the model from Tabler (2000): $\mathbf{Q} = 1500(\mathbf{C_r})(\mathbf{S_{we,AS}})(1\text{-}0.14^{\mathbf{F}/3000})$. $\mathbf{C_r}$ of 0.17 was assumed for all sites, representing the statewide average recommended for New York (Tabler 2000). $\mathbf{S_{we,AS}}$ in the $\mathbf{Q}$ model was estimated from Tabler (2000): $\mathbf{S_{we,AS}} = (-695.4 + 0.076\text{*Elevation} + 17.108\text{*Latitude})(0.10)$ and the output of this model was converted from inches to meters.

L was estimated using the model adapted from Tabler (2003): $\mathbf{L} = ([10.5 + 6.6(\mathbf{Q}/\mathbf{Q_c}) + 17.2(\mathbf{Q}/\mathbf{Q_c})^2]/34.3)(12 + 49\mathbf{P} + 7\mathbf{P}^2 - 37\mathbf{P}^3)(\mathbf{H_{req}})$. Required fence height ($\mathbf{H_{req}}$) in the **L** model was estimated from Tabler (2003): $\mathbf{H_{req}} = (\mathbf{Q}/8.5)^{0.455}$. The **L** model in the current study was modified from the original notation in two ways. Output values in Tabler (2003) are in abstract terms of **L**/**H**, or drift length relative to fence height. Units of meters are more meaningful when evaluating snow trapping function and required setback distances, so **L/H** values were multiplied by $\mathbf{H_{req}}$ to convert the model output into meters. Using $\mathbf{H_{req}}$ as a conversion coefficient (as opposed to observed **H**) is considered the correct method based on Heavey's (2013) review of Tabler (2003). Secondly, $\mathbf{Q}/\mathbf{Q_c}$ is used in the current study in place of $\mathbf{A}/\mathbf{A_e}$, which Tabler (2003) describes as equivalent and substitutable ratios (Heavey 2013). Standard setback (**D35**) was estimated from Tabler (2003): $\mathbf{D35} = 35\mathbf{H_{req}}$.

Plant growth variables of **H** and **P** were compared to the predictor variable **YAP** using simple linear regression for all fences and by vegetation type for shrub willows and conifers. A positive linear relationship between **YAP** and **H**, and a negative linear relationship between **YAP** and **P** was expected. Non-linear regression was preformed for $\mathbf{Q_c}/\mathbf{Q}$ versus **L** to evaluate the relationship between capacity/transport ratio and drift length. A quadratic regression was preformed for **YAP** versus **L** to estimate drift length in various years after planting, which was then compared to **D** and **D35** for each fence/site. All statistical analysis and figures were produced using Minitab 16.2.

3. Results

LSF were measured at 18 sites across New York State (Table 1) including ten shrub willow, six conifers, one corn, and one honeysuckle. The number of years after planting (**YAP**) ranged from one to eleven. There was a significant ($p < 0.001$) positive linear relationship between **YAP** and height (**H**) as expected (Fig. 2). When grouped by vegetation type, willow LSF had a higher R^2 value than conifer at 0.831 and 0.421 (Table 2). **H** of conifer LSF was both higher and lower than willow of equal and similar

YAP. Sardinia-corn-1 had the lowest **H** of any fence. Manheim-honeysuckle-8 had substantially less **H** than willow and conifer LSF of similar **YAP**.

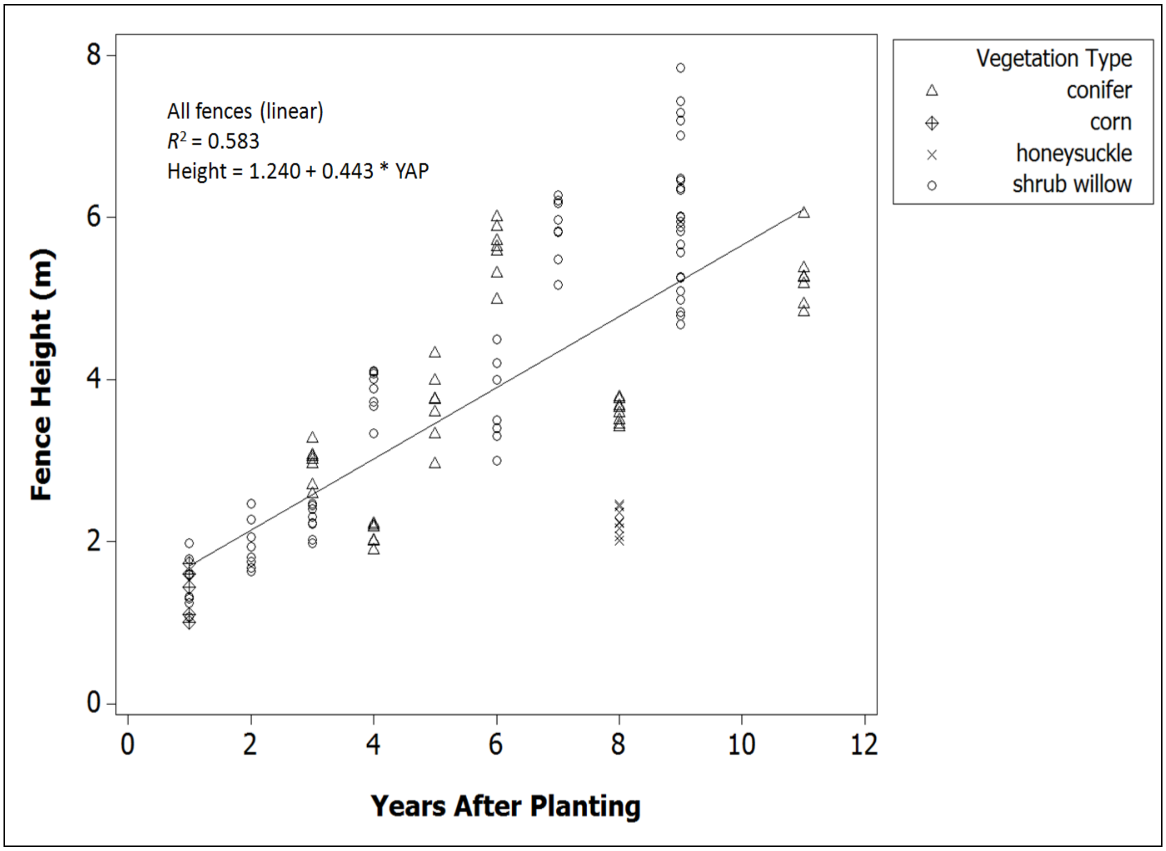

Fig. 2 Years after planting (**YAP**) versus height (**H**) for 18 living snow fences

Table 1 Mean and (standard error) for height, porosity, fetch and setback of 18 living snow fences in New York State

Taxonomy *Scientific* (common)	Fence ID Tag Town-vegetation-YAP	H Height m	P Porosity %	F Fetch m	D Setback m
Salix spp (shrub willow cultivars)	Paris-willow-1	1.5 (0.11)	92 (1.0)	109 (25.0)	26 (3.4)
Salix spp (shrub willow cultivars)	Beerston-willow-2	1.9 (0.11)	88 (1.1)	128 (5.7)	27 (0.3)
Salix spp (shrub willow cultivars)	Hamburg-willow-3	2.3 (0.06)	77 (2.0)	780 (325.1)	28 (1.3)
Salix spp (shrub willow cultivars)	Tully-A-willow-4	3.9 (0.09)	61 (1.6)	750 (36.6)	42 (0.9)
Salix spp (shrub willow cultivars)	Tully-B-willow-6	3.3 (0.07)	61 (2.5)	185 (0.0)	10 (0.0)
Salix spp (shrub willow cultivars)	Tully-C-willow-6	4.2 (0.07)	62 (1.3)	185 (0.0)	10 (0.0)
Salix spp (shrub willow cultivars)	Grand-Gorge-willow-7	5.9 (0.14)	47 (2.7)	171 (25.0)	95 (14.7)
Salix spp (shrub willow cultivars)	Preble-A-willow-9	5.0 (0.08)	33 (3.9)	480 (0.0)	13 (0.0)
Salix spp (shrub willow cultivars)	Preble-B-willow-9	5.9 (0.09)	39 (1.6)	370 (0.0)	10 (0.0)
Salix spp (shrub willow cultivars)	Preble-C-willow-9	7.0 (0.20)	26 (3.5)	538 (0.0)	9 (0.0)
Picea abies (Norway spruce)	Columbia-conifer-3	2.9 (0.08)	27 (3.0)	855 (0.0)	52 (0.0)
Picea pungens (blue spruce)	Chautauqua-conifer-4	2.1 (0.04)	61 (0.5)	620 (0.0)	59 (0.0)
Picea pungens (blue spruce)	Pomfret-conifer-5	3.6 (0.17)	41 (1.7)	437 (0.0)	31 (0.0)
Pseudotsuga menziesii (Douglas fir)	Spencerport-conifer-6	5.6 (0.11)	29 (1.9)	157 (10.7)	37 (0.6)
Thuja occidentalis (white cedar)	Gabriels-conifer-8	3.6 (0.05)	39 (1.3)	470 (59.4)	17 (0.0)
Abies concolour (white fir)	Cobleskill-conifer-11	5.3 (0.13)	38 (3.0)	318 (64.2)	41 (0.6)
Zea mays (corn)	Sardinia-corn-1	1.3 (0.09)	0 (0.0)	340 (0.0)	71 (0.0)
Lonicera tatarica (honeysuckle)	Manheim-honey-8	2.2 (0.06)	63 (2.5)	206 (18.3)	38 (0.3)

Table 2 Regression results for 18 living snow fences of various years after planting (**YAP**) and vegetation types

Linear	Vegetation Type	DF	p value	R^2	Regression Equation
YAP versus **H**	all	143	<0.001	0.583	**H** = 1.240 + 0.443 * **YAP**
YAP versus **H**	shrub willow	79	<0.001	0.831	**H** = 0.864 + 0.575 * **YAP**
YAP versus **H**	conifer	47	<0.001	0.421	**H** = 1.950 + 0.307 * **YAP**
YAP versus **P**	all	135	<0.001	0.396	**P** = 0.630 - 0.025 * **YAP**
YAP versus **P**	shrub willow	79	<0.001	0.866	**P** = 0.994 - 0.073 * **YAP**
YAP versus **P**	conifer	47	0.659	-	-
YAP versus Q_c	all	17	<0.001	0.535	Q_c = -42.1 + 36.5 * **YAP**

Non-linear	Vegetation Type	DF	p value	S	Regression Equation
Q_c/Q versus **L**	all	17	0.006	4.037	**L** = 7.693 +18.884 * exp(-0.192 * Q_c/Q)

Quadratic	Vegetation Type	DF	p value	R^2	Regression Equation
YAP versus **L**	all	17	<0.001	0.396	**L** = 32.430 - 6.100* **YAP** + 0.370^2

There was a significant ($p < 0.001$) negative linear relationship between **YAP** and optical porosity (**P**) as expected (Fig. 3). Sardinia-corn-1 was excluded from this regression because **P** was 0% ±0% (nonporous) one **YAP** making it a distinct outlier. The R^2 of this regression was low at 0.396 due to differences between shrub willow and conifer LSF. **YAP** versus **P** for willow LSF was significant ($p < 0.001$) with an R^2 of 0.866. **YAP** versus **P** for conifer LSF was not significant ($p = 0.659$), indicating that porosity did not change three to eleven **YAP** for this vegetation type. **P** of conifer LSF was generally less than willow LSF of similar **YAP**. **P** of Manheim-honeysuckle-8 was higher (more porous) than willow and conifer LSF of similar **YAP**.

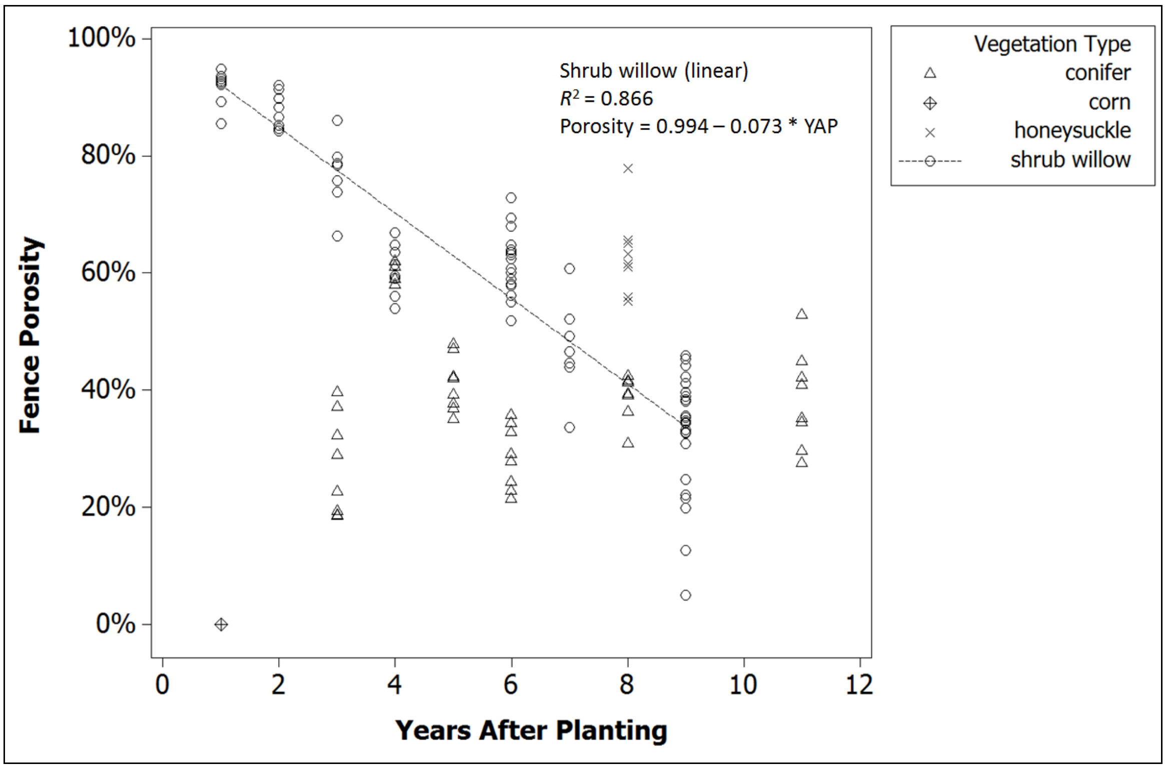

Fig. 3 Years after planting (**YAP**) versus optical porosity (**P**) for 18 living snow fences

Combined **H** and **P** data produced estimated fence capacity (**Q_c**) ranging from <1 - 430 t/m (Table 3). There was a significant ($p < 0.001$) positive linear relationship between **Q_c** and **YAP** (Fig. 4). Snow transport (**Q**) estimates ranged from 3 **-** 19 t/m and were substantially smaller than **Q_c** at most sites creating large capacity/transport ratios (**Q_c/Q**). Sardinia-corn-1 and willow LSF one and two **YAP** had **Q_c/Q** less than 1:1. Willow and conifer LSF both had **Q_c/Q** greater than 1:1 three **YAP**, meaning that three growing seasons after planting, storage capacity was greater than average annual snow transport. Shrub willow, conifer and honeysuckle LSF four to eleven **YAP** had $\mathbf{Q_c/Q}$ between 3:1 and 110:1.

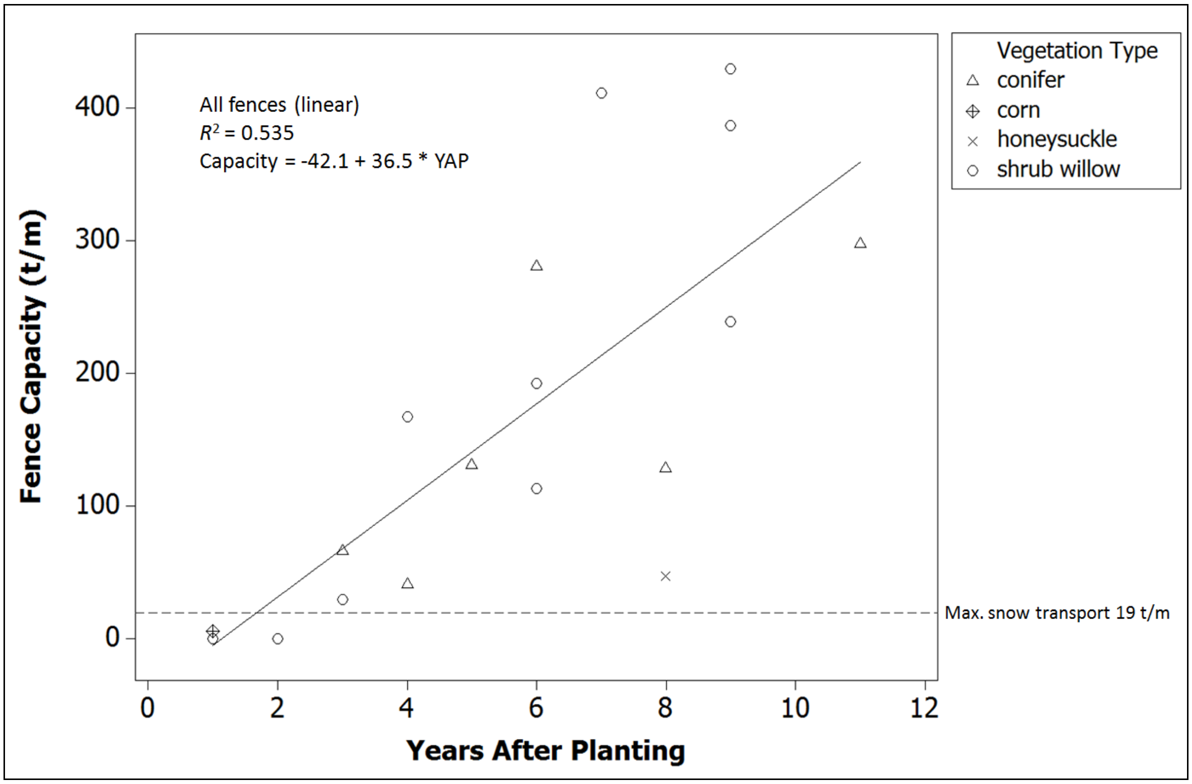

Fig. 4 Fence capacity ($\mathbf{Q_c}$) of 18 living snow fences ranged from 1 - 430 t/m. Capacity exceeded the maximum snow transport (**Q**) at any site of 19 t/m just three years after planting (**YAP**) and capacity continued to increase in a linear trend four to eleven **YAP**.

Table 3 Estimated snow trapping potential and drift length of 18 living snow fences in New York State [a]

	Q_c	Q	Q_c/Q	L	D35	D35/L
Fence ID Tag	**Fence Capacity**	**Snow Transport**	**Capacity/ Transport Ratio**	**Downwind Drift Length**	**Standard Setback**	**Standard Setback/ Estimated Drift**
Town-vegetation-YAP	t/m	t/m	x:1	m	m	x:1
Paris-willow-1	<1	8	<1	34	30	0.9
Beerston-willow-2	<1	3	<1	20	18	0.9
Hamburg-willow-3	29	19	1.5	30	46	1.5
Tully-A-willow-4	167	13	13	13	38	2.9
Tully-B-willow-6	113	4	30	7	22	3.1
Tully-C-willow-6	192	4	50	7	22	3.1
Grand-Gorge-willow-7	411	4	110	7	22	3.1
Preble-A-willow-9	239	7	34	9	33	3.7
Preble-B-willow-9	387	9	44	8	29	3.6
Preble-C-willow-9	430	10	43	8	32	4.0
Columbia-conifer-3	66	15	4	12	41	3.4
Chautauqua-conifer-4	40	12	3	16	37	2.3
Pomfret-conifer-5	130	7	19	9	28	3.1
Spencerport-conifer-6	280	3	82	5	21	4.2
Gabriels-conifer-8	128	17	8	14	43	3.1
Cobleskill-conifer-11	297	8	39	9	30	3.3
Sardinia-corn-1	5	7	<1	18	29	1.6
Manheim-honey-8	47	5	10	8	24	3.0

a: reported $\mathbf{Q_c}$ and **Q** values are rounded to the nearest whole number. $\mathbf{Q_c/Q}$ is the rounded ratio of actual $\mathbf{Q_c}$ and **Q** values

There was a significant ($p = 0.006$) asymptomatic relationship between $\mathbf{Q_c/Q}$ and **L** (Fig. 5). Based on the trend of all LSF, $\mathbf{Q_c/Q}$ approximately 15:1 or greater was consistently correlated with **L** values less than 10 m. **L** ranged from 5 - 34 m with a mean of 13 m. Observed setback (**D**) ranged from 9 - 95 m with a mean of 34 m. Setback using the standard protocol (**D35**) ranged from 18 - 46 m with a mean of 30 m.

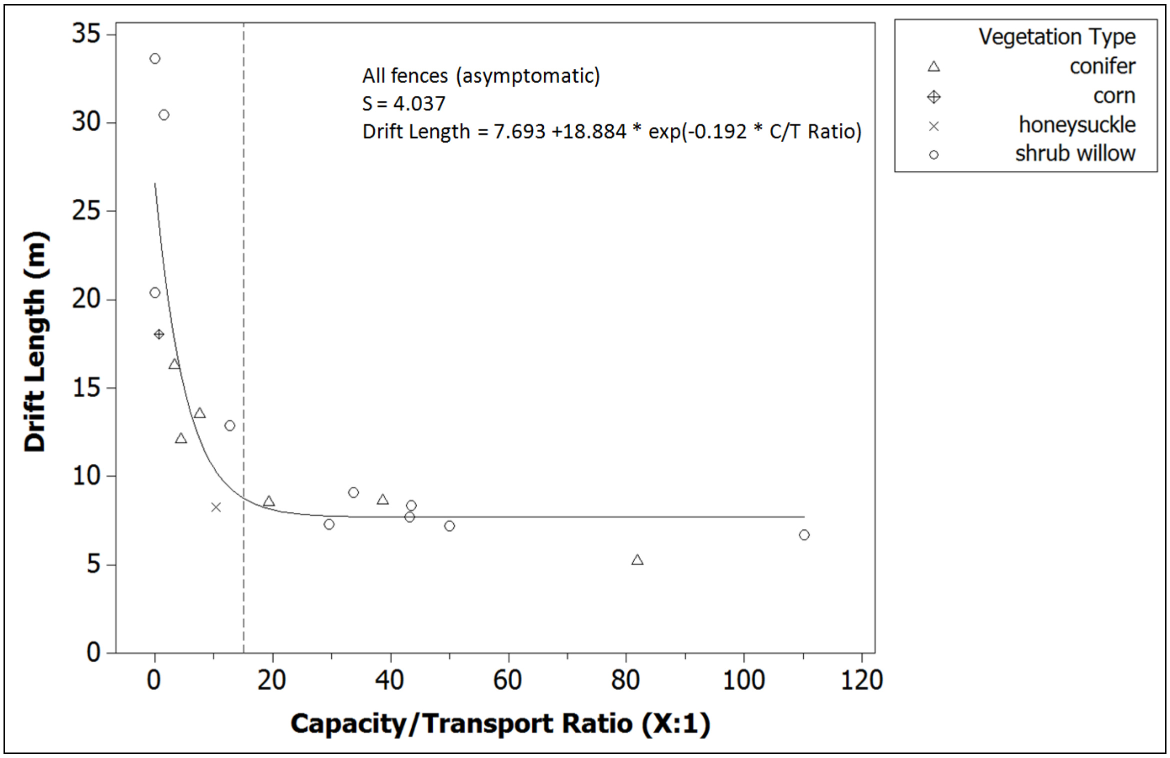

Fig. 5 Capacity/transport ratio ($\mathbf{Q_c/Q}$) versus downwind drift length (**L**) for 18 living snow fences of various vegetation types and years after planting (**YAP**). When $\mathbf{Q_c/Q}$ exceeds 15:1 the estimated drift length is less than 10 m.

There was a significant ($p < 0.001$) quadratic relationship between **YAP** and **L** amongst all LSF (Fig. 6). Drift lengths less than 10 m associated with $\mathbf{Q_c/Q}$ >15:1 occurred five **YAP** and later. **L** was less than **D** and **D35** for 15 of 18 LSF, with newly planted willow LSF being the only exceptions. Dividing the standard setback by estimated drift length (**D35/L**) showed that the standard protocol for LSF produced setbacks three to four times larger than the estimated drift length for fences four **YAP** and older (Table 3).

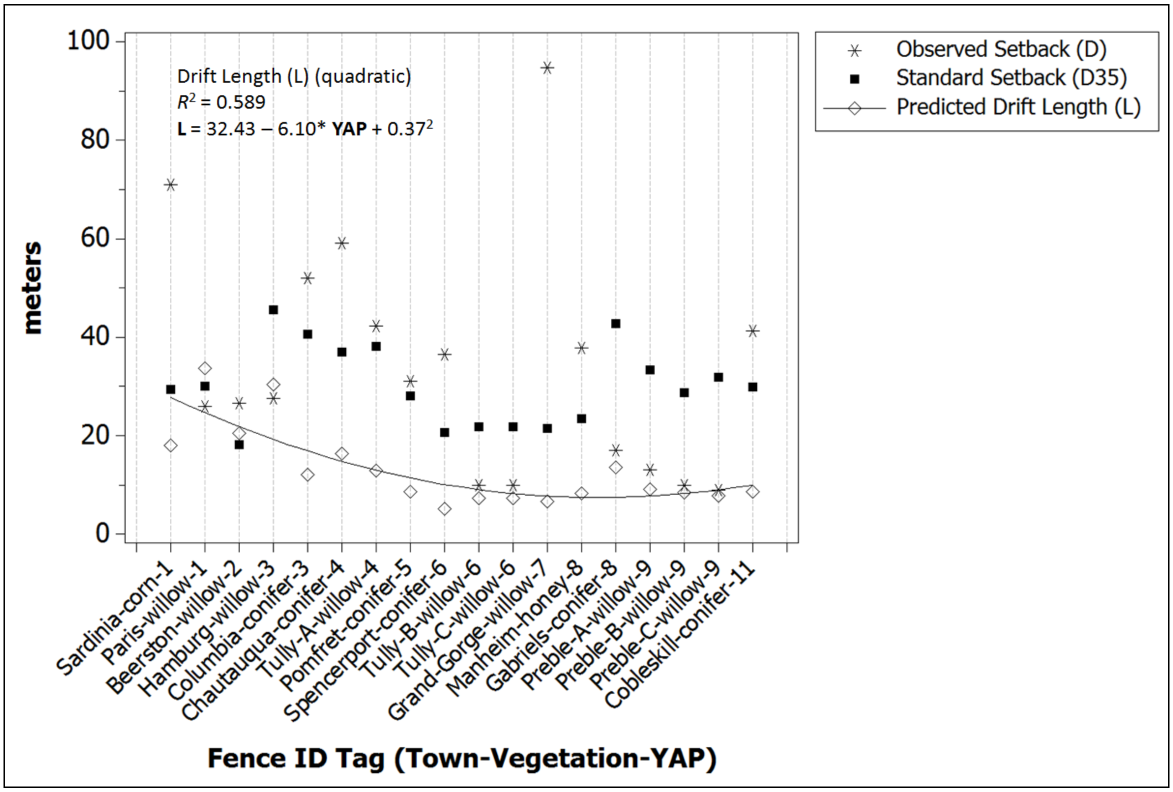

Fig. 6 The standard setback protocol (**D35**) was three to four times greater than estimated drift length (**L**) for LSF of various vegetation types in New York State four years after planting and later.

4. Discussion

4.1 Plant Growth and Snow Trapping Potential

Height (**H**) and optical porosity (**P**) are the key plant growth variables influencing snow trapping potential of LSF. The number of years after planting until **H** and **P** are sufficient to create snow trapping capacity (**Q_c**) greater than snow transport (**Q**) is an important factor in the functionality and design of LSF. This study showed that **H** and **P** growth of conifer and shrub willow LSF created capacity/transport ratios (**Q_c/Q**) greater than 1:1 as early as three years after planting (Fig. 7). This confirms previous assessments (Volk et al. 2006; Kuzovkina and Volk 2009) that noted shrub willow’s rapid growth rate and high stem counts should produce snow trapping potential two to three years after planting with proper establishment. The results of the current study differ from most literature which generally states LSF require five to seven years or longer before snow trapping begins (Tabler 2003; USDA 2011).

Fig. 7 Four years after planting, height (**H**) of living snow fence Tully-A-willow-4 was 3.9 m, porosity (**P**) was 61%, and the resulting estimated snow storage capacity (**Q_c**) was167 t/m. Average annual snow transport (**Q**) at the site was 13 t/m, creating capacity/transport ratio (**Q_c/Q**) 13:1 and estimated downwind drift length (**L**) of 13 m.

Q_c/Q greater than 1:1 shortly after planting was due to the rapid growth of shrub willow LSF, the use of large (1 - 2 m) planting stock for conifer LSF, and the use of best practices for installation and management. **Q** was less than 20 t/m across all sites - classified as "very light" (<10 t/m) or "light" (10 - 19 t/m) blowing snow conditions by Tabler (2003). Higher **Q** combined with slower growing plants, smaller planting stock, or a lack of best practices would increase the amount of time for **Q_c/Q** to exceed 1:1. Powell et al. (1992) reported an extreme case in which LSF in Wyoming required 20 years before becoming fully effective in snow transport conditions of approximately 100 t/m. However, willow and conifer LSF four and five **YAP** had $\mathbf{Q_c}$ >100 t/m in the current study, and eight LSF had $\mathbf{Q_c}$ sufficient for "severe" conditions up to 320 t/m (Tabler 2003). This indicates that with proper plant selection and other best practices, $\mathbf{Q_c/Q}$ can exceed 1:1 creating snow trapping potential several years earlier than commonly reported, even on sites with higher snow transport. The use (or lack) of best practices is a critical factor influencing the number of years required for $\mathbf{Q_c/Q}$ to exceed 1:1. This includes a comprehensive suite of practices starting with site assessment through post-installation monitoring and maintenance (see Gullickson et al. 1999; Tabler 2003; Heavey and Volk 2013). Numerous LSF where best practices had not been employed were observed during the site selection phase of this study and the stunted growth and high mortality that resulted did not create height or porosity adequate for substantial trapping potential.

Shrub willow LSF managed using best practices may improve the function and economic efficiency of LSF due to unique plant characteristics that continue to be developed through breeding programs for woody biomass production and alternative applications (Volk et al. 2006; Smart and Cameron 2008; Serapiglia et al. 2012). The cost of willow LSF is low relative to other vegetation types because willow can be propagated from unrooted stem cuttings inserted into properly prepared ground at high planting densities. The estimated cost of installation *and* maintenance of a shrub willow fence in average site conditions is approximately $20,000/km (Heavey and Volk 2012). By comparison, Walvatne (1991) reported the cost of installation contracts for LSF of other vegetation types in Minnesota between $53,000/km and $212,000/km (2013 US$). Other contracts for LSF have been reported at $25,000/km in Iowa (Shaw 1989), and $38,000/km in Colorado (Powell et al. 1992) who also reported the cost of "Wyoming" style structural snow fences 4.3 m in height to be $68,000/km. Willow showed more consistent **H** and **P** trends than conifer LSF, which may allow for more exacting design, but the willow LSF investigated had design input from one or both authors creating consistency of management practices which may account for some of the predictability. Conifer LSF were located in multiple regions under the care of various local transportation residencies and different management practices which would contribute to more inconsistent patterns of development.

The one corn fence investigated had $\mathbf{Q_c/Q}$ less than 1:1 due to small **H** (1.3 m) caused by the maximum of one growing season for this annual vegetation type and wet snow that broke off the tops of the plants, a phenomenon also observed by Shulski & Seeley (2001). The multiple rows of corn left standing also resulted in 0% **P**, which further reduces $\mathbf{Q_c}$. The honeysuckle fence investigated had $\mathbf{Q_c/Q}$ of 10:1 eight **YAP**, but less $\mathbf{Q_c}$ than willow and conifer LSF of similar **YAP**. The honeysuckle plant morphology created a large bottom gap in the fence which likely allows some amount of snow to blow through the fence without being trapped. Overall, the large $\mathbf{Q_c/Q}$ soon after planting for most fences in this study has important implications for the function and design of LSF. $\mathbf{Q_c/Q}$ greater than 1:1 causes drift growth to terminate prior to maximum equilibrium length (35H), resulting in reduced drift lengths and setback requirements.

4.2 Drift Length and Setback

The selection of setback distance for LSF is complicated by the fact that plants grow over time. Setback distance should accommodate the entire length of the downwind drift but not be excessively large. When LSF grow to large heights, $\mathbf{Q_c/Q}$ can substantially exceed 1:1 and the length of the downwind drift and required setback distance are reduced. Tabler’s (2003) standard setback protocol for LSF (**D35**) slightly modifies the protocol established for structural snow fences (35H), but does not fully account for increasing $\mathbf{Q_c/Q}$ over time. Drift formation around LSF occurs in stages over the course of a drift accumulation season as wind turbulence and drift growth alternates between the upwind and downwind side of the fence (Tabler 2003). As these alternating stages progress and the quantity of snow in the drift increases, height of the snow drift at first increases faster than the length of the drift. Once drift height reaches the approximate height of the fence in the early stages of formation, drift length then begins to extend further downwind from the fence toward the road. The $\mathbf{Q_c/Q}$ values much larger than 1:1 estimated in this study cause drifts to terminate in the early stages of formation when downwind length is only a fraction of the maximum 35H (Tabler 2003). The greater the $\mathbf{Q_c/Q}$, the shorter drift length will be because the fence only fills to a small percentage of its maximum snow holding capacity (Tabler 2003).

Based on the output of estimated drift length (**L**) for the fences investigated in this study, when $\mathbf{Q_c/Q}$ is greater than 15:1, **L** is consistently less than 10 m, which occurred five **YAP** and later. This correlation between drift length and capacity/transport ratio is likely synonymous with the first stage of drift formation before the drift builds to the height of the fence and begins to extend downwind toward the road [see Tabler (2003) and Heavey (2013) for a more in-depth explanation of drift growth dynamics]. Quantitative design protocols that account for changing capacity and drift length over time have not been integrated into extension publications and the **L** values in this study are expectedly less than observed setback distances (**D**) and calculated setbacks using the standard protocol (**D35**). **D35** was three to four times larger than **L** for LSF four **YAP** and older and **D** was even larger in most cases. Several of the willow LSF designed with input from the authors had setback distances much closer to the predicted drift length and have been reported effective by transportation staff in mitigating blowing snow problems since being installed, but setbacks of many LSF in the field are substantially larger than necessary. While extensive information and protocols for quantifying and selecting setback distances exist for structural snow fences, similar protocols for LSF are more complicated and less complete (Nixon et al. 2006), but are currently being developed (Heavey and Volk 2013).

Setback of structural snow fences is selected using Tabler's (2003) 35H and modifications to this protocol. Key assumptions of 35H are that fences are constructed to known height and porosity specifications that create capacity equal to or greater than snow transport; and fence capacity does not change over time. 35H has been mistakenly applied to the anticipated *mature* height of LSF, disregarding the impact of capacity/transport ratio and creating setback distances far too large. Tabler (2003) and a limited number of other publications (Blanken 2009) provide a slightly modified version of 35H with the **D35** protocol, in which **D35** = 35$\mathbf{H_{req}}$. Using $\mathbf{H_{req}}$ instead of mature height reduces setback based on snow transport, but does not account for changes in $\mathbf{Q_c/Q}$ over time. Most extension and other publications aimed at selecting appropriate setback for LSF are vague and inaccurate. These sources provide broad ranges and excessively large recommendations (30 - 185 m) with little or no quantitative protocols (Table 4).

Table 4 Setback recommendations for LSF from various publications are often broad ranging, excessively large and not supported by quantitative protocols

Source	Setback Recommendation	Quantitative Protocol
Heavey and Volk (2013)	Estimated drift length in chosen design year	Yes
CSU Extension (2013)	>60 m	No
NYSDOT (2012)	30 – 60 m	No
USDA (2011)	30 – 185 m	No
CCE (2011)	60 – 90 m	No
Blanken (2009)	35$\mathbf{H_{req}}$	Yes
Barkley (2008)	>30 m	No
Bratton (2006)	45 – 75 m	No
SDDA (2004)	>50 m	No
Josiah and Majeski (2002)	Not specified	No
Shulski and Seeley (2001)	$\mathbf{D} = \mathbf{H}\ (\sin\alpha)\ (12 + 49\mathbf{P} + 7\mathbf{P}^2 - 37\mathbf{P}^3)$	Yes
Streed and Walton (2001)	30 – 150 m	No
Gullickson et al. (1999)	$\mathbf{L/H} = (12 + 49\mathbf{P} + 7\mathbf{P}^2 - 37\mathbf{P}^3)$	Yes
Shaw (1989)	>60 m	No
Shaw (1988)	Not specified	No

The current study offers potential for improved quantitative design protocols, but the estimated $\mathbf{Q_c/Q}$ and **L** values produced should be validated with future research that measures snow drifts around LSF in the field. This was originally planned for the current study but was unable to be completed due to frequent warm ups and rain events during the winter of 2012/2013 that negated any substantial drift growth. If validated, Tabler's (2003) **L** model or the **YAP** versus **L** regression equation produced in this study can be used to estimate required setback based on drift length in any chosen "design year". This allows drift length in various years after planting to be modeled to inform the design process. An appropriate design year and corresponding setback distance can then be selected, taking into consideration site specific factors, knowledge of the chosen plant species, and the long term snow control goals for the site. For example, if a shrub willow fence on a given site is expected to have capacity/transport ratio of 20:1 five years after planting, and the corresponding drift length is estimated at 8 m, a setback of 12 m might be considered acceptable and selected in order to locate plants on the far edge of the transportation right of way and ensure that drifts around the fence do not encroach on the roadway. In the years prior to the fence reaching 20:1 $\mathbf{Q_c/Q}$, traditional snow controls would still be required and temporary (plastic) snow fences could be installed upwind of the living fence to mitigate the possibility of the drift extending onto the roadway. This approach could potentially accommodate LSF installations on many sites where blowing snow problems exist but planting space is limited due to right of way constraints or other planting limitations. The selection of setback distance should be as precise as possible (neither too large nor too small) to accommodate the entire length of the downwind drift, reduce the possibility of "near-snow problems" between the fence and road, and avoid unnecessary land acquisitions for additional planting space.

An important factor when considering reduced setback distances is exceedance probability, or the chance that snow transport will exceed fence capacity and/or create a longer than anticipated drift length in winters with above average snow loads or prior to the fence achieving a large $\mathbf{Q_c/Q}$. If $\mathbf{Q_c/Q}$ substantially exceeds 1:1, a fence is unlikely to fill to capacity even in the most extreme winters, but drift length may still exceed predicted $\mathbf{L}$. The probability of a drift accumulation season in which $\mathbf{Q}$ is twice the average is less than 0.1% (Tabler 2003). $\mathbf{Q_c/Q}$ of 2:1 would therefore have sufficient capacity for this rare scenario and LSF with $\mathbf{Q_c/Q}$ greater than 2:1 would have a reduced drift length. Similarly, the snow relocation coefficient ($\mathbf{C_r}$) of 0.17 assumed for every site in this study could be higher at any given site or even double the assumed value as estimated at 0.35 in Shulski and Seeley (2001), which may increase the number of years until $\mathbf{Q_c/Q}$ exceeds1:1 and drift length is reduced. Hypothetically doubling $\mathbf{C_r}$ for every site in the current study would double the $\mathbf{Q}$ value at all sites and reduce $\mathbf{Q_c/Q}$ by half, but willow and conifer LSF would still have $\mathbf{Q_c/Q}$ >1:1 four years after planting, and 4:1 to 54:1 five to eleven years after planting. In general, large amounts of excess storage capacity soon after planting appear to mostly offset the potential impacts of above average winters and lessen the importance exceedance probabilities. Continued testing and refinement of these scenarios and design protocols is a pertinent area of future research, in conjunction with field studies to validate models of plant growth, snow storage capacity and drift length.

5. Conclusion

LSF can reduce the cost of snow control and improve highway safety by trapping blowing snow in drifts before it reaches the road, providing economic, social and environmental benefits. The key plant growth variables for snow trapping of height (**H**) and optical porosity (**P**) were measured on 18 LSF of various vegetation types and years after planting. **H** increased linearly over time and **P** decreased linearly for willow LSF, but did not change for conifer LSF. Three years after planting, conifer and willow LSF had capacity/transport ratios ($\mathbf{Q_c/Q}$) greater than 1:1, indicating snow trapping potential sooner than reported in most publications. The use of best practices is critical in creating this early snow trapping potential. Four to eleven years after planting, $\mathbf{Q_c/Q}$ was between 3:1 and 110:1 indicating large excess storage capacity relatively early in the potential life cycle of the fences. Doubling the estimated snow transport did not substantially reduce the large amounts storage capacity, indicating that these results are applicable to a wider geographic area than New York State where snow transport conditions may be higher. Estimated drift length (**L**) was consistently less than 10 m when $\mathbf{Q_c/Q}$ exceeded 15:1. This occurred five years after planting and is much smaller than most setback distances observed in the field and recommended in current publications. The results of this study can improve quantitative design protocols for LSF making fences more effective and facilitating installations on more sites through reduced setback distance based on estimated drift length. Future research should seek to validate estimates of $\mathbf{Q_c/Q}$ and **L** with field measurements and incorporate research results into extension publications for the improved design, function and adoption of LSF.

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