

Shrub-Willow Living Snow Fences Impact on Soil Carbon and Nitrogen Pools and their Lability

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Abstract

Shrub-willow (*Salix* spp.) living snow fences are an effective agroforestry practice for reducing blowing snow on roadways while providing ecosystem services such as soil carbon (SOC) sequestration and bioenergy feedstock production. Despite these benefits, research on SOC accumulation in willow systems is limited. This study aimed to evaluate the impact of different willow varieties on SOC and total nitrogen concentrations, stratification, and lability in marginal soil. A randomized complete block design with three willow varieties (*Salix purpurea* 'Fish Creek,' *S. purpurea* × *S. miyabeana* 'Oneonta,' and *S. caprea* × *S. cinerea* 'S365') and control plots was used. Post-planting weed management included herbicide and manual control. Two years post-planting, composite soils were collected from geo-referenced sites within each plot at 0- to 90-cm depths and analyzed for SOC, total N, microbial biomass carbon (SMBC), metabolic quotient (qR), active C, cold and hot-water carbon (CWC & HWC), particulate organic carbon and nitrogen (POC & PON). All willow varieties, especially Fish Creek and Oneonta, significantly increased SOC and total N contents. Willow treatments positively influenced labile SOC and total N pools, with notable increments in SMBC, POC, and PON. Stratification of SOC and total N decreased with depth, particularly up to 0–45 cm. Carbon and nitrogen management indices (CMI & NMI) varied significantly among willow treatments, highlighting their potential to enhance SOC sequestration and total N dynamics. This study provides insights into the positive impact of specific willow varieties on soil properties, emphasizing the importance of SOC sequestration in managing marginal soils.

Introduction

Global climate change adaptation and mitigation efforts have highlighted agroforestry systems as a proactive approach, integrating fast-growing, highly adaptable short-rotation shrubby and small woody plants with traditional agronomic crops to utilize marginal lands for enhanced ecosystem services (Dhyani et al. 2021). In cold-weather regions worldwide, the implementation of living snow fences is a specific agroforestry practice aimed at controlling blowing and drifting snow on transportation routes (Heavey et al. 2018; Qi et al. 2020). Serving as windbreaks, living snow fences consist of linear rows of trees and/or shrubs, disrupting blowing snow particles and trapping them in drifts around the fence before reaching roads (Shaw 1988).

Living snow fences often incorporate various tree and shrub species, such as dogwoods (*Cornus* spp.), honeysuckles *Lonicera periclymenum*), pines (*Pinus* spp.), poplar (*Populus* spp.), and spruces (*Picea* spp.). Recently, shrub-willows, recognized as a short-rotation woody crop (Volk et al. 2006), have gained popularity due to their versatile adaptability on marginal soil, easy establishment, fast growth, high-density planting arrangements, and cost-effectiveness compared to other species used in living snow fences (Heavey and Volk 2014; Ogdahl et al. 2016). Furthermore, willow can yield useful biomass, holding potential applications as bioenergy feedstocks and for other purposes (Zamora et al. 2014).

In addition to their role as living snow fences, shrub-willows contribute a perennial source of litterfall and deep, well-distributed root biomass. These roots translocate a diverse array of organic compounds below-ground, enhancing soil quality (Nair et al. 2009). Woody plant-derived organic compounds, including lignin, are crucial for soil organic carbon (SOC) storage, as they exhibit longer mean residence times in the soil compared to most crop residues (Medinski et al. 2014). The longer harvesting cycles of woody plantations also result in reduced soil disturbances compared to agronomic crops (Udawatta and Jose 2012). While there is existing research on the impact of shrub-willows in short rotation woody crop plantations for biomass production, limited work has been done to assess their effects on soil organic carbon (SOC) dynamics in living snow fence arrangements (Lockwell et al. 2012; Udawatta and Jose 2012).

SOC serves as a core ecological indicator influencing soil and environmental functions (Schmidt et al. 2011; Lehman and Kleber 2015; Amoakwah et al. 2022). It comprises a complex mixture of carbonaceous constituents derived from living plant roots, microbes, detritus, and highly decomposed materials. SOC supports biodiversity, regulates chemical reactions, provides physical stability to improve ecosystem resilience and services (Amoakwah et al. 2022; Islam et al. 2022). However, considering SOC as a homogeneous pool overlooks variations in chemical composition and relative proportions of its individual pools, impacting and reflecting management practices (Islam et al. 2022).

SOC contains diverse pools with variable turnover rates, and their relative proportions are associated with inputs, temporal changes, and land-use systems (Amoakwah et al. 2022). The labile pool, with faster turnover rates, includes active C, microbial biomass C (SMBC), potentially mineralizable C (PMC), light-fraction, cold and hot-water extractable C (CWC and HWC), Anthrone reactive C (ARC), particulate organic C (POC), and beta-glucosidase activity. Various metabolic quotients and indices have been suggested as sensitive indicators of SOC dynamics (Knight and Dick 2004; Luce et al. 201; Hamkalo and Bedernichek 2017; Islam et al. 2022).

Given the stoichiometric link between carbon and nitrogen in soil organic matter (SOM), labile N-associated soil properties such as microbial biomass N (SMBN), active N, particulate organic N (PON), and potentially mineralizable N (PMN) play important roles in soil functional properties (Asner 1997; Luce et al. 2013; Islam et al. 2022). These labile SOC and total N pools act as reservoirs for microbes and provide early indications of management-induced changes in SOC and total N dynamics (Amoakwah et al. 2022; Islam et al. 2022). As there is growing interest in SOC sequestration for offsetting greenhouse gas emissions and climate change effects, it remains unclear whether willow living snow fence plantings influence SOC and total N accumulation and their lability to improve soil functional properties.

A comprehensive understanding of SOC and total N pools and their lability, particularly in response to different shrub-willow varieties under land-use changes, may offer insights into marginal land management implications for potential SOC sequestration. Our hypothesis is that in a temperate climate, the conversion of weed-infested right-of-way marginal land into shrub-willow living snow fences would

impact site conditions, influencing SOC and total N accumulation, stratification, and their lability. This impact would be driven by factors such as residue placement, input amounts and quality, and frequency of disturbances over time. The study aims to (1) determine the depth distribution of pH, electrical conductivity (EC_e), SOC, total N, CWC, HWC, SMBC, active C, POC, and PON pools; (2) assess the effect of depth distribution on stratification of SOC and total N pools; and (3) evaluate whether observed differences translate into SOC lability.

Materials and Methods

Site description

The study was established on the Minnesota Department of Transportation (MnDOT) right-of-way on the north side of U.S. Highway 14 (44°03'32" N; 93°31'12" W) in Waseca, Minnesota, USA, which is adjacent to the University of Minnesota Southern Research and Outreach Center. The climate of Waseca is characterized by warm summers and cold winters, with an average temperature and precipitation of 7.1°C and 91 cm, respectively (NCDC 2015). Soils are associations of Clarion (Fine-loamy, mixed, super active, mesic Typic Hapludolls), Cordova (Fine-loamy, mixed, super active, mesic Typic Argiaquolls), Glencoe (Fine-loamy, mixed, super active, mesic Cumulic Endoaquolls), and Nicollet (Fine-loamy, mixed, super active, mesic Aquic Hapludolls) series (NRCS 2004). Soils are very deep and well-drained to very poorly drained which formed from calcareous till.

Experimental design and cultural practices

The study site ranges in slopes between 0 and 5% and consisted primarily of weeds, such as Canada thistle (*Cirsium arvense* Scop.), common ragweed (*Ambrosia artemisiifolia* L.), and annual grasses (e.g., *Setaria* spp.). Prior to establish the study, the site was sprayed with 1.3 kg ha⁻¹ a.i. glyphosate [N-(phosphonomethyl)glycine] to control annual and perennial weeds. The site was rotary tilled to a depth of about 10 cm, a week before planting willows. Plots were aligned approximately 40 m from the edge of the highway; at this distance, we assumed impacts from the highway (e.g., winter salt spray) would be negligible on plant growth and soil properties.

A randomized complete block design was established with three willow varieties *Salix purpurea* 'Fish Creek', *S. purpurea* × *S. miyabeana* 'Oneonta', and *S. caprea* × *S. cinerea* 'S365' in planting arrangements of two rows replicated four times. Control plots (no willow plantings) were also established along the living snow fence. Willow varieties were selected based on their fast establishment and ability to produce a high number of stems in previous willow trials and experiments in Minnesota (Gamble et al. 2014; Zamora et al. 2014).

Willow cuttings were obtained from Double A. Willow Inc., in Fredonia, New York, USA. The site was planted manually with 20-cm-long dormant willow stem cuttings to a depth of about 14 cm 18.3 m long x 2.3 m wide plots. Willows planted within rows were spaced 60 cm apart and plants between rows were spaced 76 cm resulting in 31 plants per row. All plots were aligned along their northern-most row to

create a continuous upwind snow fence edge. Additionally, between-plot spacing was the same as within-row spacing to prevent any gap effects on snow drifting (Tabler 2003). Shortly after planting, the site was managed for post-emergent weeds. Plots were sprayed with 0.3 kg/ha *a.i.* clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) and 0.2 kg/ha *a.i.* sethoxydim {2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one}. Additionally, plots were subjected to manual weed control throughout the remainder of the growing season.

Soil collection, processing, and analyses

Two years after planting of willows, three soil cores at 0–90 cm depth were collected from geo-referenced points within each replicated plot by a hand-held auger (internal diam. 10 cm) using systematic sampling technique. Soil cores were then composited at 0–15, 15–30, 30–45, 45–60, 60–75, and 75–90 cm, respectively, for replicated plot, and stored in sealable plastic bags. A portion of the field-moist soil was sieved through a 2-mm mesh to remove visible rock fragments and large crop residues followed by incubation in sealable plastic bags at room temperature ($\sim 25^{\circ}\text{C}$) for 7 days to stabilize biological activities prior to analyze for biological properties. The other portion of the field-moist soil was air-dried under shade at room temperature for 15 days, ground and 2-mm sieved prior to analyses.

Soil microbial biomass carbon (SMBC) was measured by following the rapid microwave irradiation and extraction method (Islam and Weil 1998) as follows:

$$\text{SMBC (mg/kg)} = C_{\text{EXT}} / K_{\text{ME}}$$

Where the C_{EXT} is a flush of C from the difference between the extracted organic C in microwaved soil (C_{EXTMW}) minus the extracted organic C in field-moist unmicrowaved soil (C_{EXTUMW}), and the K_{ME} is 0.213, the fraction of the SMB extracted by neutral 0.5M K_2SO_4 as C_{EXT} . Both C_{EXTMW} and C_{EXTUMW} concentrations were determined by using Shimadzu[®] TOC-L/Total N-L analyzer.

The metabolic quotient (qR) was calculated by dividing the SMBC with the soil total organic carbon (SOC) content. The SOC and total N concentrations were determined on finely ground (< 0.125 mm) air-dried soil by using Thermo-Fisher[®] FLASHEA 1112 Series automated dry combustion CN analyzer. Active C concentration was measured spectrophotometrically at 590 nm upon mild oxidation of SOC with neutral 0.2 M KMnO_4 solution (Weil et al. 2003). Both cold and hot-water C were also extracted on separate soil samples and determined using a Shimadzu[®] total dissolved SOC/Total N analyzer (Hamkalo and Bedernichek 2017).

To determine particulate organic carbon (POC) and nitrogen (PON), the particulate organic matter (POM) was collected after dispersing the 2-mm sieved air-dried soil with 0.5% Na-hexametaphosphate solution (Cambardella and Elliott 1992). The dispersed soil suspension was passed through a 53- μm sieve to collect sand associated POM followed by washing with running distilled water and oven-drying at 65°C until a constant weight was obtained. A portion of the sand associated POM was ground by a ceramic mortar and pestle and analyzed for POC and PON concentrations using Thermo-Fisher[®] FLASHEA 1112

Series automated dry combustion CN analyzer. Soil pH in distilled deionized water and 2M KCl (1:2) was determined by a glass electrode. The ECe (1:1 soil and water paste) was determined by an electrical conductivity probe.

Soil organic carbon and nitrogen stratification

Stratification of carbon and nitrogen pools was calculated by dividing their values at different depths under willow living snow fences with the respective values of that carbon and nitrogen in soils under the control 75 to 90 cm depth (Franzluebbers 2002). The use of control soil lower depth (as a control) to calculate for carbon and nitrogen stratification assessment is important, so that the impact of willow living snow fences under similar soil and climate conditions can be compared.

Soil carbon and nitrogen lability and management indices

By accounting the data on all SOC pools, carbon management index (CMI) was calculated (Blair et al. 1995; Islam et al. 2021).

$$\text{CMI} = (\text{CPI} \times \text{C}_{\text{Li}}) \dots\dots\dots (1)$$

Where, CPI is the C pool index and C_{Li} is the C lability index. The CPI and the C_{Li} were calculated as:

$$\text{CPI} = [\text{TOC in treatment soil} / \text{TOC in reference soil}] \dots\dots\dots (2)$$

$$\text{C}_{\text{Li}} = [\text{C}_{\text{L}} \text{ in treatment soil} / \text{C}_{\text{L}} \text{ in reference soil}] \dots\dots\dots (3)$$

Where, C_{L} refers to the lability of C, which was calculated as:

$$\text{C}_{\text{L}} = [\text{Labile C} / \text{Non-labile C}] \dots\dots\dots (4).$$

By using the principle of CMI calculation, nitrogen management index (NMI) was calculated (Islam et al. 2021).

$$\text{NMI} = (\text{NPI} \times \text{N}_{\text{Li}}) \dots\dots\dots (5)$$

Where, NPI is the N pool index and N_{Li} is the N lability index.

$$\text{NPI} = [\text{Total N in treatment soil} / \text{Total N in reference soil}] \dots\dots\dots (6)$$

$$\text{N}_{\text{Li}} = [\text{NL in treatment soil} / \text{NL in reference soil}] \dots\dots\dots (7)$$

Where, NL refers to the lability of N, which was calculated as:

$$\text{NL} = [\text{Labile N} / \text{Non-labile N}] \dots\dots\dots (8)$$

While the labile C pool was considered as the portion of SOC that was measured as CWC, HWC, SMB, active C, and POC, respectively, the labile N pool was considered as the portion of total N that was

separated as PON. The non-labile C and N pools were calculated by subtracting the labile C and N pools from the SOC and total N concentrations.

Statistical analyses

The SAS 9.4 (SAS, 2013) was used to perform two-way analysis of variance to evaluate the effects of willow variety and soil depth, along with their interactions as fixed variables, on soil carbon and nitrogen pools. Where effects were significant, individual treatment means and interactions were tested for significant difference via Duncan's multiple range test (DMRT) to control Type I comparison-wise error rates. For all analyses, $\alpha \leq 0.05$ was considered significant. All the results were expressed based on oven-dried soil equivalent weight.

Results and Discussion

Soil pH and electrical conductivity

Soils under Fish Creek and Oneonta willow treatments had significantly higher pH values, based on water or salt-solution, compared to the control; however, pH values under S365 and the control were statistically similar (Table 1). In contrast, the ECe did not vary significantly among the soils under willow treatments. Both pH and ECe values significantly decreased with soil depth without a significant willow x soil depth interaction.

The increased pH values suggest an influence of Oneonta and Fish Creek willow varieties on the soil pH environment. Conversely, the pH values under S365 and the control were statistically similar, suggesting that these particular willow treatments did not induce a significant change in soil acidity. While the pH levels experienced alterations, the overall salinity, as reflected by ECe, remained consistent. However, the absence of significant interactions between willow treatments and soil depth for both pH and ECe indicates that these changes were not uniquely influenced by the presence of willow varieties.

Table 1

Effects of willow living snow fence treatments on pH, electrical conductivity, and total organic carbon (SOC) and total nitrogen concentration at different soil depths.

Snow fence	Soil depth	pH _{H2O}	pH _{KCl}	ECe	SOC	Total N
treatment	(cm)	(1:2)	(1:2)	(dS/cm)	(g/kg)	
Control	0–90	7.0c ^δ	5.8c	283.0a	18.7b	1.49c
Fish Creek	0–90	7.4b	6.2b	282.6a	26.9a	2.02a
Oneonta	0–90	7.8a	6.6a	249.5a	25.4a	1.71b
S365	0–90	7.1bc	5.9bc	216.4a	24.7a	1.76b
Snow fence x soil depth						
Control	0–15	6.9	6	364.4	31.6	2.58
	15–30	7	5.9	321.3	28.4	2.28
	30–45	7	5.8	267.1	21.8	1.72
	45–60	6.9	5.6	261.4	13.8	1.08
	60–75	7.1	5.7	254.7	8.9	0.68
	75–90	7	5.6	228.9	7.6	0.6
Fish Creek	0–15	7.5	6.6	372.1	44.1	3.76
	15–30	7.3	6.3	302.3	40.6	3.21
	30–45	7.3	6.2	252.8	29	2.18
	45–60	7.2	5.9	171	21.2	1.38
	60–75	7.4	5.9	420.3	15.4	0.89
	75–90	7.7	6.4	177.4	11	0.69
Oneonta	0–15	7.4	6.7	353.1	42.4	3.27
	15–30	7.7	6.6	290.9	37.6	2.84
	30–45	7.6	6.6	278.6	25.3	1.78
	45–60	7.7	6.4	164.4	18	1.04
	60–75	8	6.7	197.3	15.2	0.71
	76–90	8.2	6.8	212.6	13.8	0.59
S365	0–15	7.3	6.6	385.8	39.2	2.9
	15–30	7.1	6	250.5	36.3	2.51

Snow fence	Soil depth	pH _{H2O}	pH _{KCl}	ECe	SOC	Total N
	30–45	7.2	5.9	213.9	28.2	2.15
	45–60	7	5.5	146.6	18.5	1.24
	60–75	6.9	5.6	150	15.1	1
	75–90	7.4	5.9	151.4	11.2	0.73
(P < F)						
Soil depth		0.28	0.036	0.003	0.001	0.001
Snow fence x soil depth		0.94	0.98	0.9	0.961	0.476
^δ Means under each column separated by same lower-case letter are not significantly different among the snow fence treatments at p < 0.05.						

Soil carbon and nitrogen contents

Fish Creek, Oneonta, and S365 willow varieties significantly increased SOC contents by 32–44% compared to the control (Table 1). A similar, slightly less pronounced impact was observed on total N contents, with non-significant differences among willow varieties. Willow treatments positively influenced labile SOC and total N contents, including CWC, HWC, SMBC, active C, POC, and PON. Fish Creek, Oneonta, and S365 varieties notably increased SMBC, POC, and PON contents relative to the control (Tables 1 & 2; Fig. 1). However, qR (SMBC: SOC), representing the size of biological C pool, did not exhibit significance (Fig. 2). While CWC, HWC, SMB, and active C contents under willow varieties were similar, POC and PON contents differed significantly. All SOC and total N pools significantly decreased with depth, particularly up to 0–45 cm depth. However, HWC, SMBC, qR, active C, and PON contents were influenced by the interaction between willow varieties and soil depth.

A higher SOC content under fast-growing willow treatments can be attributed primarily to the surface accumulation of a larger amount of litterfall and increased translocation of root-derived carbon in undisturbed, moist, cold, and anaerobic soil conditions (Amoakwah et al. 2022). The reduced contact between microbes and the surface-accumulated unfragmented litterfall may have favored the dominance of the fungal food web under willow treatments (Beare et al. 1992; Amoakwah et al. 2022). The unique characteristics of fungal food webs, such as slow decomposition of residues and higher carbon-use efficiency, make the transformation of plant-derived carbon into SOC pools through humification processes more biologically efficient under willow treatments compared to the control (Islam and Weil 2000). It is reported that root-derived carbon contributes more to stable SOC pools than an equivalent amount of surface litterfall-derived carbon due to limited oxygen diffusion in the soil (Ross 1989; Kätterer et al. 2011). Our studied soil, primarily clay loam, retains more moisture, restricting soil aeration and expectedly slowing down the decomposition of residues and native SOC with an associated increase in the residence time of residual carbon to accumulate as SOC. The SOC content under willow treatments may also be increased by an increase in recalcitrant carbon-enriched inputs (e.g., lignin) or

stabilization by clays via polyvalent cation-organic carbon bridging. Soils with a greater clay content tend to allow for faster adsorption of carbon compounds, providing greater protection from opportunistic microbial catabolism (Medinski et al. 2014). Similarly, a significantly higher total N content under willow treatments is related to the C:N stoichiometry in SOM and the contribution of biological nitrogen fixation by leguminous herbs and weeds.

Table 2

Effects of snow fence treatments on cold- (CWC) and hot-water carbon (HWC), particulate organic carbon (POC), active carbon (AC), and particulate organic nitrogen (PON) concentration at different soil depths.

Snow fence	Soil depth	CWC	HWC	AC	POC	PON
treatment	(cm)	(mg/kg)			(g/kg)	
Control	0–90	25.9b ^δ	62.4b	227.9b	0.82b	0.06b
Fish Creek	0–90	37.9a	93.7a	293.9a	1.64a	0.11a
Oneonta	0–90	36.5a	91.1a	278.9a	1.52a	0.08ab
S365	0–90	35.0a	92.2a	277.2a	1.09ab	0.12a
Snow fence x soil depth						
Control	0–15	45.9	123.8	643.9	2.68	0.19
	15–30	36.3	90.9	398.4	1.27	0.09
	30–45	27.6	62.9	197	0.49	0.02
	45–60	18.6	41.8	72.9	0.24	0.01
	60–75	16.2	32.9	28.2	0.13	0.01
	75–90	10.8	21.9	27	0.09	0.01
Fish Creek	0–15	60.2	212.5	805.8	4.04	0.39
	15–30	54.6	136.1	479.5	3.01	0.18
	30–45	43.4	95.1	253	1.38	0.05
	45–60	31.3	60.7	123.7	0.71	0.02
	60–75	24.4	37.2	54.1	0.47	0.02
	75–90	13.8	20.5	47.2	0.25	0.01
Oneonta	0–15	56.8	210.8	784.5	4.49	0.26
	15–30	47.7	133.8	450.1	2.58	0.14
	30–45	43.2	88.8	235.8	1.01	0.05
	45–60	33.5	57.4	109.2	0.55	0.02
	60–75	20.4	33.8	48	0.28	0.01
	75–90	17.5	22.3	45.6	0.18	0.01
S365	0–15	58.1	219.8	784.4	3.01	0.42
	15–30	48.9	133.3	452.2	1.79	0.17

Snow fence	Soil depth	CWC	HWC	AC	POC	PON
	30–45	42.6	89.1	230.9	0.85	0.06
	45–60	30.9	60.3	105.8	0.43	0.03
	60–75	18.5	32.8	47.5	0.27	0.01
	75–90	11	18	42.4	0.2	0.01
(P < F)						
Soil depth		0.001	0.001	0.001	0.001	0.001
Snow fence x soil depth		0.83	0.001	0.001	0.845	0.026
^δ Means under each column separated by same lower-case letter are not significantly different among the snow fence treatments at p < 0.05.						

The expected increase in labile carbon and nitrogen pools under willow treatments is driven by the increases in SOC and total N content. The significant increases in the SMBC pool are associated with a higher amount of labile carbon-based energy sources, such as root exudates and turnover, supporting higher SMBC populations under willow treatments than the control (Baum et al. 2009). This suggests that SMBC efficiently utilizes more carbon for cell growth than for maintenance and survival, supporting a large SMBC population. Willows are known to increase SMBC, especially mycorrhizal fungi on arable land (Baum et al. 2009), essential components of soil microbial communities (Rooney et al., 2009; Hryniewicz et al. 2012). Truu et al. (2009) reported increased SMBC under *S. viminalis* and *S. dasyclados* clones after 2 years of establishment. POC and PON, resultant products of plant residue decomposition and microbial metabolites, increased with SMBC activity, suggesting that willow varieties drove their increase (Islam et al. 2021). Changes in SMBC, POC, PON, and increases in active C, signaling labile carbon from plant residue, and SMBC, indicate improved soil quality (Weil et al. 2003; Islam et al. 2022). An increase in SMBC drove the noted increase of POC, PON, and active C after willow growth. No other studies have assessed the effect of willows on active C specifically. CWC and HWC contents increased under willow treatments due to slower and incomplete decomposition of residues by SMBC under moist and partially anaerobic conditions, similar to our experimental site. Previous studies have reported SOC increase under short rotation woody crops (SRWC) afforestation and in clay soils (Lockwell et al. 2012; Thiel et al. 2015. Rytter 2016; Ile et al. 2023).

An increase in SOC under SRWC afforestation has been noted by several previous studies (Jug et al. 1999; Lafleur et al. 2015). Jug et al. (1999) noted a 10 to 90% increase in SOC content in the first 0- to 10-cm under different SRWC afforestation, including *S. viminalis*, 7 to 10 years after planting. Likewise, Lafleur et al. (2015) observed a 25% increase in SOC content in the first 0- to 10-cm of soil under 2- to 6-year-old *S. miyabeana* 'SX67' plantings compared to reference sites. Previous study results noted the highest SOC under sites with the highest clay and clay + silt content than those of the light-textured soils

(Medinski et al. 2014; Lafleur et al. 2015). A higher clay content in our site may thus have been a contributor to the SOC accumulation shortly after willow planting, despite initial site preparation.

Conversely, other studies have reported a decrease or no significant changes in SOC content in 0- to 45-cm depth of silt-loam soil across a chronosequence of *S. x dasyclados* 'SV1' in central New York State, USA (Pacaldo et al. 2013). They suggested this was because of well-drained characteristics of silt loam textured soil, which with good aeration easily oxidized SOC in response to opportunistic microbial catabolism.

A significant decrease in SOC and total N contents with soil depth may have resulted from surface litterfall accumulation, decreased rhizosphere activity, and shallow root depth due to lack of any physical disturbances or plowing of the soil (Sundermeier et al. 2011). Willow treatments showed higher SOC and total N contents than the control down to about 45 to 60 cm depth, suggesting an increase in labile SOC and total N contents. The causes of significant differences observed in POC, total N, and PON contents among willow varieties may be related to species-specific differences in litterfall and root characteristics (Hangs et al. 2014).

Soil carbon and nitrogen stratification

While the SOC pools exhibited increased stratification under all willow treatments compared to the control, total N stratification significantly increased (by 32%) only under Fish Creek, relative to the control (Table 3). Among the labile SOC pools, the highest POC stratification occurred under both Fish Creek and Oneonta (1.8- to 2-fold higher) compared to s365 and the control. In contrast, PON stratification significantly increased (> 2-fold) under both s365 and Fish Creek, followed by Oneonta (1.5-fold), compared to the control. SOC and total N pools showed decreased stratification with depth, especially for POC and active C, with a significant willow x depth interaction. However, most stratification was observed up to 0–45 cm soil depth.

Table 3

Effects of willow snow fence treatments on stratification of total organic (SOC), cold (CWC), hot-water extractable (HWC), microbial biomass carbon (SMBC), active carbon (AC), particulate organic carbon (POC), total nitrogen, and particulate organic nitrogen (PON) pools at different soil depths.

Snow fence	Soil depth	Stratification of carbon and nitrogen pools							
treatment	(cm)	SOC	Total N	CWC	HWC	SMBC	POC	AC	PON
Control	0–90	2.5b	2.2b ^d	2.4b	2.8b	3.3b	8.9c	8.4b	7.7c
Fish Creek	0–90	3.5a	2.9a	3.5a	4.3a	5.0a	17.7a	10.9a	15.5a
Oneonta	0–90	3.3a	2.5ab	3.4a	4.2a	4.9a	16.4a	10.3a	11.4b
S365	0–90	3.3a	2.5ab	3.2a	4.2a	5.1a	11.8b	10.3a	16.1a
Snow fence x soil depth									
Control	0–15	4.2	3.7	4.2	5.7	7.0	29.0	23.8	26.8
	15–30	3.7	3.3	3.4	4.2	4.9	13.7	14.7	12.8
	30–45	2.9	2.5	2.6	2.9	3.2	5.3	7.3	2.9
	45–60	1.8	1.6	1.7	1.9	2.1	2.6	2.7	1.7
	60–75	1.2	1.0	1.5	1.5	1.5	1.4	1.0	1.2
	75–90	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0
Fish Creek	0–15	5.8	5.4	5.6	9.7	13.6	43.7	29.8	54.1
	15–30	5.3	4.6	5.1	6.2	7.3	32.5	17.7	24.3
	30–45	3.8	3.2	4.0	4.3	4.6	14.9	9.4	7.4
	45–60	2.8	2.0	2.9	2.8	2.6	7.6	4.6	3.3
	60–75	2.0	1.3	2.3	1.7	1.1	5.1	2.0	2.4
	75–90	1.5	1.0	1.3	0.9	0.6	2.7	1.7	1.2
Oneonta	0–15	5.6	4.7	5.3	9.6	13.7	48.6	29.0	35.9
	15–30	4.9	4.1	4.4	6.1	7.7	27.9	16.7	20.0
	30–45	3.3	2.6	4.0	4.1	4.1	11.0	8.7	6.5
	45–60	2.4	1.5	3.1	2.6	2.1	6.0	4.0	2.6
	60–75	2.0	1.0	1.9	1.5	1.2	3.1	1.8	1.8
	75–90	1.8	0.9	1.6	1.0	0.4	1.9	1.7	1.6

Snow fence	Soil depth	Stratification of carbon and nitrogen pools							
S365	0–15	5.2	4.2	5.4	10.0	14.4	32.6	29.0	57.2
	15–30	4.8	3.6	4.5	6.1	7.5	19.4	16.7	23.6
	30–45	3.7	3.1	3.9	4.1	4.2	9.2	8.5	8.6
	45–60	2.4	1.8	2.9	2.8	2.6	4.7	3.9	4.1
	60–75	2.0	1.4	1.7	1.5	1.3	2.9	1.8	1.9
	75–90	1.5	1.1	1.0	0.8	0.6	2.2	1.6	1.2
(P < F)									
Soil depth		0.011	0.02	0.023	0.01	0.024	0.001	0.001	0.001
Snow fence x soil depth		0.341	0.472	0.671	0.112	0.456	0.045	0.0124	0.216
^δ Means under each column separated by same lower-case letter are not significantly different among the snow fence treatments at p < 0.05.									

The increased stratification of SOC and total N pools resulted from converting the control site to 2-years old willow living snow fences, primarily due to higher inputs of C and greater rhizosphere presence within the Ap horizon by growing roots. Additionally, the stratification of labile SOC fractions attributed to an increase in surface SOC content, which providing energy sources and favorable growing conditions for SMBC, may have contributed to higher POC, PON, active C, CWC, and HWC contents under willow treatments. With improved biological efficiency and greater adsorption of C compounds, contributing to macroaggregate formation by POC, PON and active C, and get POC and PON physically protected within soil aggregates (Grayston et al. 1997; Crow and Houston, 2004; Sauer et al. 2007; Truu et al. 2009). Several studies have reported that SOC and nutrient stratification is common in grasslands and forests as well as when plowed cropland is converted to no-till agriculture or other perennial vegetation (Schnabel et al. 2001; Sundermeier et al. 2011; Amoakwah et al. 2022). Contrary to absolute amounts, the stratification of both total and labile SOC pools in our study suggests that willows, when using as living snow fences, act as a C sink. The higher SOC stratification under willow treatments reflects a physically undisturbed environment, leading to better soil quality and enhanced ecosystem services.

Soil carbon and nitrogen lability

The CPI, serving as an indicator of SOC accumulation or depletion, exhibited variable influences from willow treatments, highlighting a significant willow x depth interaction (**Fig. 3**). Mean CPI values under Fish Creek, Oneonta, and S365 were notably higher (ranging from 52–64%) compared to the control. Similarly, NPI values were increased under willow treatments relative to the control (**Fig. 4**), with the highest value (1.38) observed under Fish Creek and the lowest (1.18) under Oneonta.

Table 4

Effects of snow fence treatments on cold- (CWC) and hot-water extractable (HWC) carbon, microbial biomass carbon (SMBC), active carbon (AC), particulate organic carbon (POC), and particulate organic nitrogen (PON) lability at different soil depths.

Snow fence	Soil depth	Lability of different carbon (CL) and nitrogen (NL) pools					
treatment	(cm)	CWC	HWC	SMBC	AC	POC	PON
Control	0–90	0.001a ^δ	0.003a	0.009a	0.010a	0.036b	0.030b
Fish Creek	0–90	0.002a	0.003a	0.008a	0.009a	0.058a	0.043ab
Oneonta	0–90	0.002a	0.003a	0.009a	0.009a	0.054ab	0.046ab
S365	0–90	0.002a	0.004a	0.010a	0.010a	0.040ab	0.057a
Snow fence x soil depth							
Control	0–15	0.002	0.004	0.012	0.021	0.099	0.086
	15–30	0.001	0.003	0.009	0.014	0.051	0.045
	30–45	0.001	0.003	0.008	0.010	0.024	0.013
	45–60	0.001	0.003	0.009	0.006	0.018	0.011
	60–75	0.002	0.004	0.009	0.004	0.014	0.013
	75–90	0.001	0.003	0.008	0.004	0.011	0.012
Fish Creek	0–15	0.001	0.005	0.017	0.019	0.107	0.114
	15–30	0.001	0.004	0.010	0.013	0.095	0.060
	30–45	0.002	0.004	0.009	0.009	0.051	0.029
	45–60	0.002	0.003	0.007	0.006	0.033	0.020
	60–75	0.002	0.003	0.005	0.004	0.034	0.020
	75–90	0.002	0.002	0.003	0.005	0.026	0.013
Oneonta	0–15	0.001	0.005	0.018	0.020	0.132	0.102
	15–30	0.001	0.003	0.011	0.013	0.082	0.061
	30–45	0.002	0.004	0.010	0.010	0.045	0.027
	45–60	0.002	0.004	0.007	0.006	0.034	0.021
	60–90	0.001	0.002	0.002	0.004	0.013	0.037
S365	0–15	0.002	0.006	0.021	0.021	0.093	0.186
	15–30	0.001	0.004	0.012	0.014	0.054	0.072

Snow fence	Soil depth	Lability of different carbon (CL) and nitrogen (NL) pools					
	30–45	0.002	0.004	0.009	0.009	0.031	0.034
	45–60	0.002	0.004	0.009	0.006	0.024	0.024
	60–75	0.002	0.003	0.005	0.003	0.019	0.014
	75–90	0.001	0.002	0.003	0.004	0.018	0.013
(P < F)							
Soil depth		0.055	0.001	0.001	0.001	0.001	0.001
Snow fence x soil depth		0.72	0.087	0.001	0.97	0.994	0.047
^δ Means under each column separated by same lower-case letter are not significantly different among the snow fence treatments at p < 0.05.							

Carbon lability (C_L), representing the ratio of labile to non-labile pools of SOC based on POC, was significantly higher only under Fish Creek and Oneonta (increased by 1.5- to 1.6-fold) than under the control (Table 4). C_L values for both Fish Creek and Oneonta were significantly higher than those for S365. Except for CWC, the C_L values of labile SOC pools showed significant variations with depth. In contrast, N_L based on PON was significantly higher in S365 (1.9-fold), followed by Fish Creek (1.4-fold) and Oneonta (1.5-fold) compared to the control. N_L of PON decreased with depth. Similarly, the C_{Li} based on POC was significantly higher (1.5- to 2.9-fold) under Fish Creek, Oneonta, and S365 compared to the control (Table 5). While C_{Li} values for HWC, SMBC, and active C significantly decreased with depth, none of the CLi values were influenced by a willow x depth interaction. The N_{Li} values for PON increased (by > 2-fold) under willow treatments relative to the control.

Table 5

Effects of snow fence treatments on cold- (CWC) and hot-water extractable (HWC) carbon, microbial biomass carbon (SMBC), active carbon (AC), particulate organic carbon (POC), and particulate organic nitrogen (PON) lability index at different soil depths.

Snow fence	Soil depth	Lability index of different carbon (CLi) and nitrogen (NLi) pools					
treatment	(cm)	CWC	HWC	SMBC	AC	POC	PON
Control	0–90	1.00a ^δ	1.00a	1.00a	1.00a	1.00c	1.00b
Fish Creek	0–90	1.19a	1.01a	0.93a	1.12a	2.93a	2.16a
Oneonta	0–90	1.31a	1.10a	1.03a	1.02a	2.28a	2.57a
S365	0–90	1.24a	1.12a	1.11a	1.07a	1.47b	2.65a
Snow fence x soil depth							
Control	0–15	1.00	1.00	1.00	1.00	1.00	1.00
	15–30	1.00	1.00	1.00	1.00	1.00	1.00
	30–45	1.00	1.00	1.00	1.00	1.00	1.00
	45–60	1.00	1.00	1.00	1.00	1.00	1.00
	60–75	1.00	1.00	1.00	1.00	1.00	1.00
	75–90	1.00	1.00	1.00	1.00	1.00	1.00
Fish Creek	0–15	1.03	1.30	1.47	0.92	1.34	2.38
	15–30	1.46	1.09	1.07	0.90	3.74	2.85
	30–45	1.21	1.13	1.20	0.96	2.88	3.04
	45–60	1.10	0.95	0.84	1.13	2.93	1.82
	60–75	1.20	0.78	0.53	1.36	3.55	1.73
	75–90	1.16	0.79	0.50	1.43	3.16	1.15
Oneonta	0–15	1.00	1.33	1.54	0.93	1.81	1.73
	15–30	1.40	1.17	1.22	0.89	2.65	2.75
	30–45	1.67	1.52	1.65	1.06	2.80	2.84
	45–60	1.72	1.35	1.06	1.17	2.64	1.92
	60–75	1.00	0.63	0.48	1.01	2.26	2.68
	75–90	1.09	0.62	0.24	1.03	1.55	3.52
S365	0–15	1.14	1.55	1.82	1.03	0.96	3.63

Snow fence	Soil depth	Lability index of different carbon (CLi) and nitrogen (NLI) pools					
	15–30	1.45	1.30	1.38	0.95	1.60	3.88
	30–45	1.42	1.25	1.27	1.00	1.39	4.00
	45–60	1.51	1.30	1.13	1.17	1.24	2.10
	60–75	1.04	0.71	0.58	1.11	1.77	1.11
	75–90	0.87	0.63	0.48	1.16	1.88	1.16
(P < F)							
Soil depth		0.201	0.001	0.001	0.001	0.38	0.089
Snow fence x soil depth	0.934	0.319	0.135	0.268	0.946	0.235	
^δ Means under each column separated by same lower-case letter are not significantly different among the snow fence treatments at p < 0.05.							

The CMI, a composite measure of SOC accumulation and lability, varied significantly among willow treatments compared to the control (Table 6). The highest CMI values were associated with POC (2.4- to 4.6-fold). Similarly, all willow treatments exceeded the control in NMI values for PON (by 2.4 to 3-fold), with no significant differences among willow treatments. CMI and NMI values based on HWC, SMBC, active C, and PON decreased with depth; however, a significant willow x depth interaction affected CMI values for SMBC.

Table 6

Effects of snow fence treatments on carbon (CMI) and nitrogen (NMI) management indices based on cold- (CWC) and hot-water extractable (HWC) carbon, microbial biomass carbon (SMBC), active carbon (AC), particulate organic carbon (POC), and particulate organic nitrogen (PON) management index at different soil depths.

Snow fence	Soil depth	Carbon and nitrogen management indices					
treatment	(cm)	CWC	HWC	SMBC	AC	POC	PON
Control	0–90	1.00b ^δ	1.00b	1.00b	1.00b	1.00c	1.00c
Fish Creek	0–90	1.78a	1.45a	1.29a	1.57a	4.59a	2.83a
Oneonta	0–90	1.80a	1.42a	1.24a	1.48a	3.20b	2.39a
S365	0–90	1.70a	1.43a	1.33a	1.40a	2.36b	2.96a
Snow fence x soil depth							
Control	0–15	1.00	1.00	1.00	1.00	1.00	1.00
	15–30	1.00	1.00	1.00	1.00	1.00	1.00
	30–45	1.00	1.00	1.00	1.00	1.00	1.00
	45–60	1.00	1.00	1.00	1.00	1.00	1.00
	60–75	1.00	1.00	1.00	1.00	1.00	1.00
	75–90	1.00	1.00	1.00	1.00	1.00	1.00
Fish Creek	0–15	1.42	1.76	1.98	1.29	2.00	3.49
	15–30	1.98	1.54	1.51	1.22	4.52	3.82
	30–45	1.76	1.53	1.52	1.33	4.16	3.92
	45–60	1.86	1.52	1.27	1.79	5.12	2.03
	60–75	1.93	1.28	0.82	1.95	6.28	2.24
	75–90	1.71	1.10	0.64	1.87	5.47	1.49
Oneonta	0–15	1.31	1.75	2.04	1.25	2.52	2.29
	15–30	1.73	1.50	1.64	1.15	3.32	3.00
	30–45	1.79	1.45	1.38	1.26	3.10	3.58
	45–60	1.99	1.49	1.10	1.64	3.24	1.86
	60–75	1.79	1.16	0.90	1.75	3.73	1.67
	75–90	2.16	1.14	0.42	1.83	3.30	1.96
S365	0–15	1.39	1.84	2.13	1.25	1.19	3.99

Snow fence	Soil depth	Carbon and nitrogen management indices					
	15–30	1.94	1.55	1.56	1.16	1.87	4.04
	30–45	1.91	1.50	1.37	1.22	2.23	4.20
	45–60	1.84	1.58	1.37	1.49	1.79	2.45
	60–75	1.63	1.15	0.93	1.65	3.59	1.68
	75–90	1.52	0.97	0.63	1.64	3.47	1.38
(P < F)							
Soil depth		0.68	0.001	0.001	0.001	0.13	0.001
Snow fence x soil depth	0.999	0.748	0.001	0.268	0.96	0.436	
^δ Means under each column separated by same lower-case letter are not significantly different among the snow fence treatments at p < 0.05.							

The significant increase in CPI and CMI values after 2 years of willow growth indicates increased SOC accumulation and improved lability. Particularly, higher C_L , C_{Li} , and CMI associated with POC relative to the control suggest that POC is an early and sensitive indicator of SOC accumulation, along with improved carbon lability (Yucel et al., 2015; Amoakwah et al., 2022; Islam et al., 2022). NPI, N_L , N_{Li} , and NMI values associated with PON also tended to increase under willow varieties, suggesting higher total N content and its lability (Amoakwah et al. 2022). The fact that N-related indices increased, albeit to a lesser extent than C-related indices, is expected due to the C:N stoichiometry of plant litter, microbes, and SOM, and the overall interdependence of C- and N-related properties in soil nutrient cycling (Asner et al. 1997; Chapin et al. 2011; Amoakwah et al. 2022). A significant willow x depth interaction on the CMI values based on SMBC is related to soil depth gradient variations in C-inputs among willow treatments, supporting SMBC's contribution to accumulating SOC with improved lability.

Conclusions

The study highlights significant increases in SOC ranging from 32–44% under all willow treatments, underscoring their positive impact on SOC sequestration. While the influence on total N was less pronounced, the analysis of labile SOC and total N pools revealed positive effects, particularly with Fish Creek, Oneonta, and S365 varieties significantly increasing SMBC, POC, and PON contents compared to the control. Both SOC and total N stratifications were greater under willow treatments, with the highest POC stratification observed under Fish Creek and Oneonta, and increased PON stratification under S365 and Fish Creek. The CMI and NMI consistently exhibited higher values for Fish Creek, Oneonta, and S365, indicating increased SOC and total N accumulation, turnover, and nutrient availability. The observed decrease in SOC and total N pools, along with their stratification and lability with depth, particularly up to 0–45 cm soil depth, suggests a concentration in the upper soil layers. The significant SOC increase

under willow treatments implies potential for long-term SOC storage enhancement. Additional comprehensive and extended studies are necessary to assess the role of willow living snow fence across different sites and age classes in sustaining soil quality and ecosystem services.

Declarations

Author Contribution

Eric Ogdahl performed soil sampling, processing, and analysis, and wrote the draft. Diomy Zamora established the experiment, performed soil sampling, and edit and review the manuscript. Khandakar Islam supervised soil analysis, data analysis and visualization, and edit and review the manuscript.

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Figures

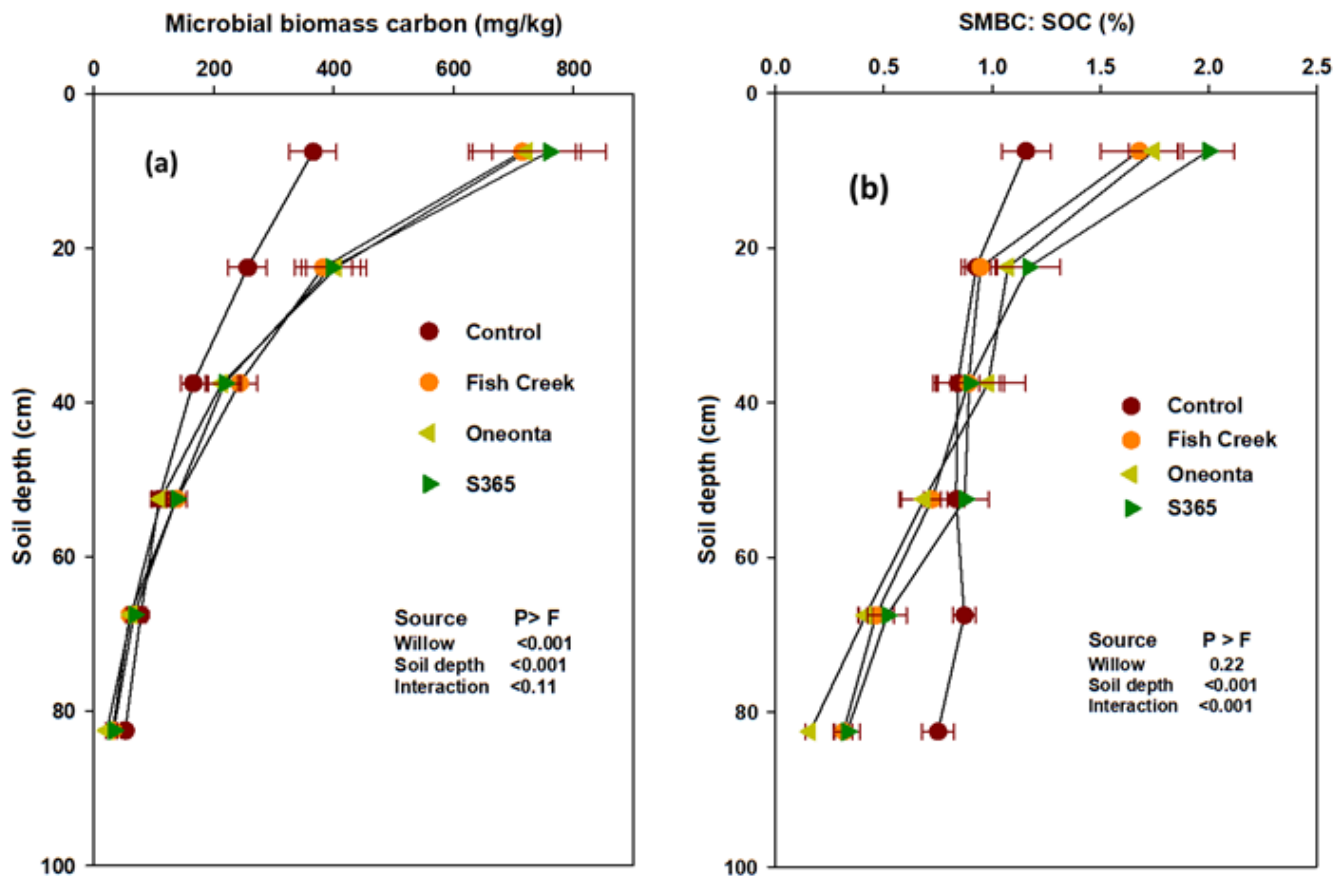


Figure 1

Shrub-willow living snow fence treatments effect on (a) total microbial biomass carbon (SMBC) and (b) metabolic quotient (total microbial biomass carbon over total organic carbon as qR) at different soil depths (mean values were presented with standard errors).

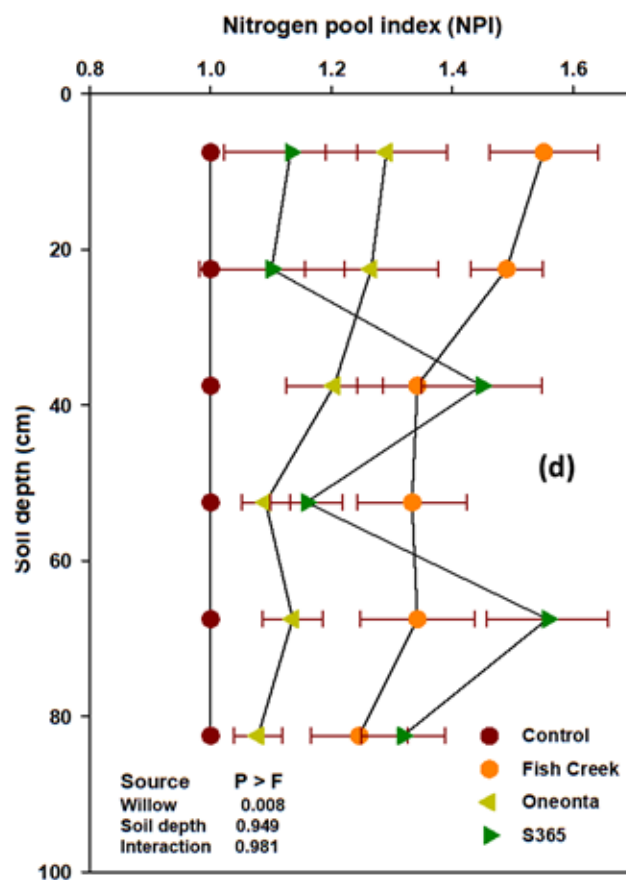
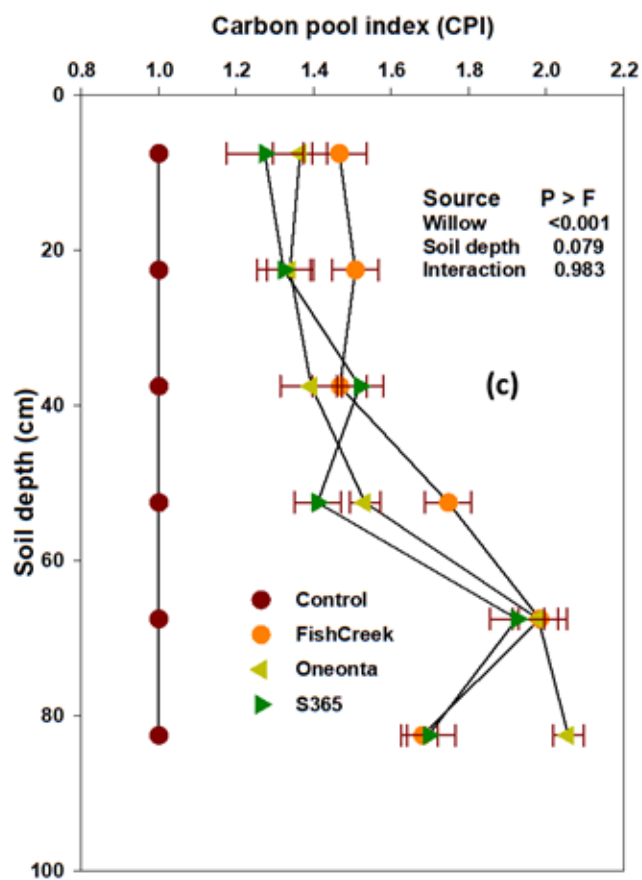


Figure 2

Shrub-willow living snow fence treatments effect on carbon (CPI) and nitrogen pool indices (NPI) at different soil depths (mean values were presented with standard errors).