Examining the Nutrient Dynamics of Willow Biomass Energy Plantations

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Abstract

Natural Resources Canada, along with a number of Canadian provinces, considers bioenergy to be a legitimate and sustainable source of energy that will constitute a significant portion of future energy production. Shrub willow (*Salix* spp.) is a proven viable purpose-grown bioenergy feedstock. The objective of this four-year study was to examine the cycling of nitrogen, phosphorus, potassium, and sulphur within several high density willow stands during the first rotation, in order to forecast the long-term sustainability of these woody crop plantations grown on numerous soil types in Saskatchewan. Soil and plant samples were collected throughout the rotation and analyzed for their nutrient content. The results of this study indicate that sites with relatively fertile soils are more capable of sustaining willow productivity for multiple rotations compared to sites with marginal soils, where supplemental fertility will be required to sustain long-term production levels. Ensuring optimal soil fertility will help promote the sustainability of these purpose-grown biomass energy plantations.

Introduction

As the world population continues to increase exponentially, the need for a reliable and sustainable source of energy is becoming more important. The use of biomass-derived energy accounts for approximately 10% of the global energy requirement (Berndes et al., 2003); however, with growing desire worldwide for a secure and environmentally friendly energy source, there is increased interest in developing biomass production systems for use as a dedicated or ‘purpose-grown’ feedstock for bioenergy production. Natural Resources Canada, along with a number of Canadian provinces, considers bioenergy to be a legitimate and sustainable source of energy that will constitute a significant portion of future energy production. The establishment of short-rotation intensive culture woody plantations, such as fast-growing shrub willow (*Salix* spp.), represents a compelling purpose-grown bioenergy crop option for diversifying farmers trying to maintain an economically viable operation, especially in the northern regions where annual crops are grown on marginal agricultural soils. Preliminary data suggests that willow could provide that option while increasing both biodiversity and carbon sequestration within the agricultural landscape. Before there is widespread adoption of willow plantations, however, there needs to be a clear understanding of willow agronomy for farmers. A fundamental question regarding willow biomass energy plantations is how sustainable are these multi-rotation production systems, in terms of long-term soil productivity, given the rapid growth rate of willow and chronic nutrient exports offsite when harvesting the biomass on short rotations. Exacerbating the issue is the probability that farmers will not take their best land out of annual crop production for these willow plantations, instead relegating them to any available marginal land to manage their risk. The objective of this study was to quantify the biogeochemical cycling of nitrogen (N), phosphorous (P), potassium (K), and sulphur (S) within willow plantations, during the first rotation, grown at four sites in Saskatchewan with different soil types, for providing insight into the long-term sustainability of these woody biomass energy production systems. A tremendous opportunity exists to develop non-consumable woody crops as a bioenergy feedstock, especially if they can be successfully grown on millions of hectares of marginal land that is deemed unsuitable for annual crop production.

Materials and Methods

Field Sites

The data for this study were collected from four willow variety trial plantations located along a 500-kilometre north-south gradient within Saskatchewan, Canada, chosen to represent the diverse soil types and climatic conditions present within the province (Fig. 1; Table 1). In the spring of 2007, six willow varieties were planted at each site in a randomized complete block design, replicated four times. The one-year-old willow varieties used in this study were provided by Dr. Tim Volk from the State University of New York College of Environmental Science and Forestry, which has been studying the cultivation and use of willow biomass as a bioenergy feedstock for more than 10 years. The six willow varieties used were: Allegany (*Salix purpurea*), Canastota (*Salix sachalinensis* x *miyabeana*), Fish Creek (*Salix purpurea*), Sherburne (*Salix sachalinensis* x *miyabeana*), SX61 (*Salix sachalinensis*), and SX64 (*Salix miyabeana*). Each varietal plot (6.3 x 7.9 m) consists of 78 plants (three double-rows of 13 plants/row), with spacings of 1.5 m between the double-rows, 0.6 m between rows within the double-row, and 0.6 m between plants within the double-row; resulting in a planting density of approximately 15,873 plants/ha (Fig. 2). In the spring of 2008, the willow plants were cut down to encourage coppicing (the production of a large number of shoots from the established root system) and were grown for an additional three years before harvesting.

Sampling and Analyses of Soils and Willow Leaf and Stem Tissues

After planting the willow at each site, three soil cores per varietal plot were collected with a back-saver probe, separated into four-inch depth increments to two feet, and composited. Additionally, bulk density cores were collected at each depth and these values were used to convert extractable soil nutrient concentrations to kg/ha (Table 2). All soil samples were air-dried to a constant weight, ground with a rolling pin, mixed, sieved (< 2 mm fraction retained), and analyzed for extractable contents of N (NO_3^--N + NH_4^+-N; 2 *M* KCl), P and K (Modified

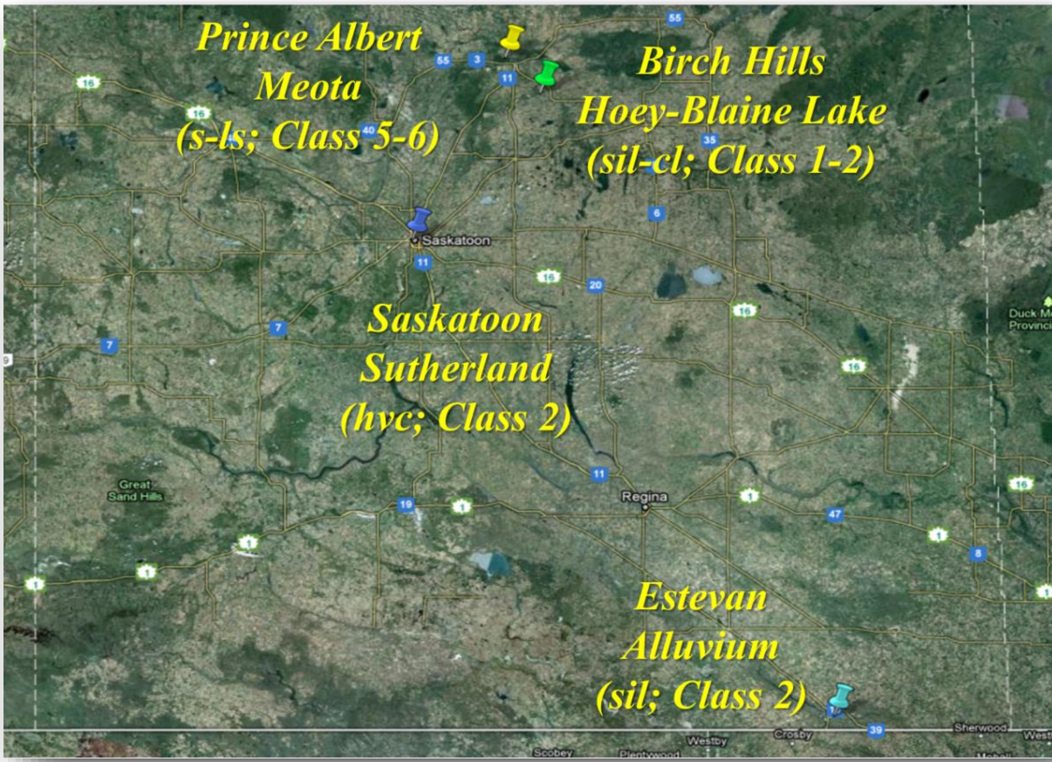

Figure 1. Locations of willow clonal trial study sites established in Saskatchewan.

Kelowna), and S (0.01M $CaCl_2$). The N, P, and S extractants were analysed colorimetrically (Technicon AutoAnalyzer; Technicon Industrial Systems, Tarrytown, NY) and K using atomic absorption (Varian Spectra 220 Atomic Absorption Spectrometer). Values of pH (1:2; soil:water) and percentages of N and organic carbon (TruSpec CNS analyzer, Leco Corporation, St. Joseph, MI) also were determined for the soils (Table 2).

The coppiced willow stems after the first growing season, along with the harvested willow stems at the end of the three-year rotation, were dried to a constant weight for biomass production estimates and then thoroughly milled and homogenized prior to analyzing a subsample for N, P, K, and S contents. Every year, total leaf biomass for each willow variety was estimated by collecting all of the leaves from three representative buffer trees within each plot in early September and extrapolated to a stand level based on planting density. Estimates of annual nutrient cycling through litterfall were determined by multiplying the nutrient concentrations of senesced willow leaves (collected from each varietal plot in November each year) by the total leaf biomass estimates. All willow tissue samples were analyzed for N, P, and K content following a H_2SO_4 digest (Thomas et al., 1967), with S content measured using a TruSpec CNS analyzer (Leco Corporation, St. Joseph, MI).

Results and Discussion

The N, P, K, and S exported from the four sites over a four-year period through the removal of willow stems, during coppicing following the establishment year in addition to harvesting the willow stems at the end of the three-year rotation, averaged 61, 9, 45, and 11

Table 1. Selected characteristics of four willow variety trial field sites located throughout Saskatchewan.

Site	Soil Characteristics			Site Characteristics					Weed Control Practices			
									Pre-planting		Post-planting	
	Association	Soil Type	Texture	Prior Crop	ACC*	MAP†	MAT‡	FFD§	Mechanical	Chemical	Mechanical	Chemical
Saskatoon**	Sutherland	Orthic Vertisol	heavy clay	barley/oats	2-3	375	2	112	Deep till	Goal 2XL (2 L ha^{-1})	Between-row tillage and hand weeding	Glyphosate (2 L ha^{-1}) Bromoxynil (0.5 L ha^{-1}) Goal 2XL (2 L ha^{-1})
Prince Albert††	Meota	Orthic Black Chernozem	sand to loamy-sand	summerfallow	5-6	450	0	85	Deep till	Goal 2XL (2 L ha^{-1})	Between-row tillage and hand weeding	Goal 2XL (2 L ha^{-1})
Birch Hills‡‡	Hoey-Blaine Lake	Orthic Black Chernozem	silt-loam to clay-loam	canola	1-2	420	1	90	Deep till	Goal 2XL (2 L ha^{-1})	Between-row tillage and hand weeding	Glyphosate (2 L ha^{-1}) Goal 2XL (2 L ha^{-1})
Estevan§§	Alluvium	Cumulic Humic Regosol	silt-loam	summerfallow	2-3	430	4	124	Deep till	Goal 2XL (2 L ha^{-1})	Between-row tillage and hand weeding	Glyphosate (2 L ha^{-1}) Goal 2XL (2 L ha^{-1})

* Agriculture capability classification (Class 1: no significant limitations; Class 2: moderate limitations; Class 3: moderately severe limitations; Class 4: severe limitations; Class 5: very severe limitations; Class 6: limited capability for arable agriculture).
† Mean Annual Precipitation (mm).
‡ Mean Annual Temperature (ºC).
§ Frost-free days.
** For a complete description (i.e., map unit, parent material, stoniness, drainage, etc.) see SCSR (1978).
†† For a complete description see SCSR (1976).
‡‡ For a complete description see SCSR (1989).
§§ For a complete description see SCSR (1997).

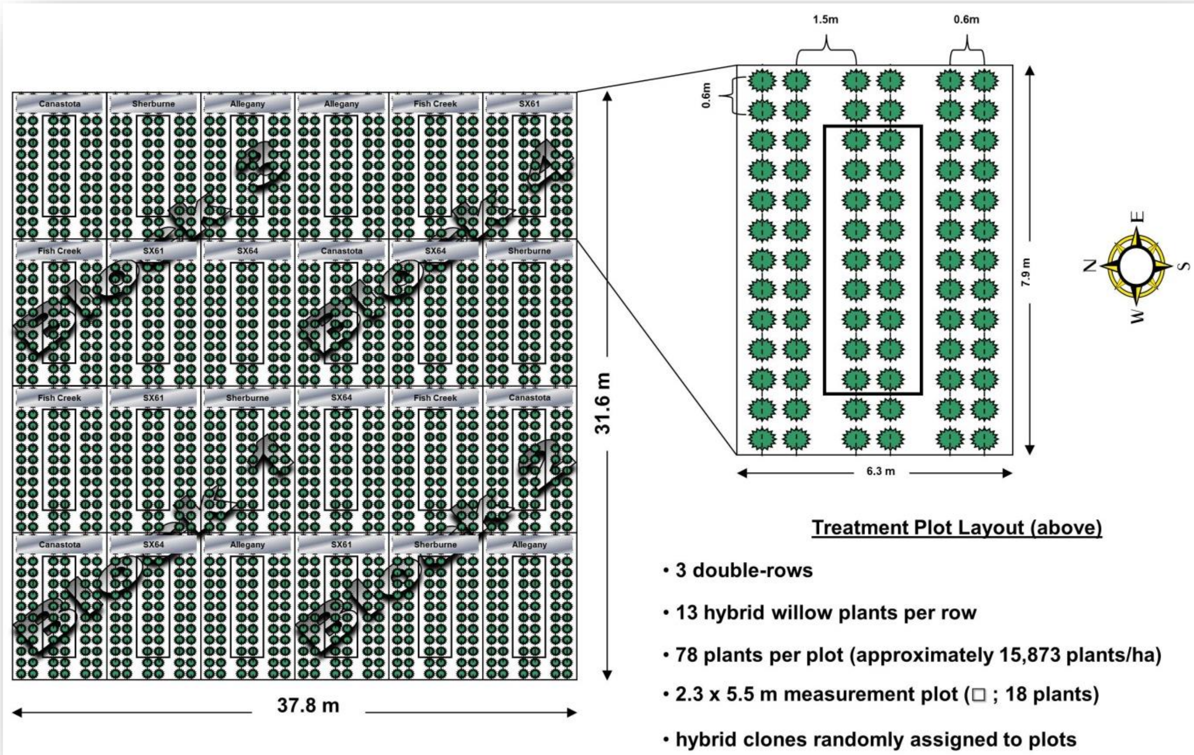

Figure 2. Experimental design used for willow clonal trial.

Table 2. Mean (n = 24) soil properties of willow sites located throughout Saskatchewan.

					Nutrients*			
	Depth		Organic C	Nitrogen	Total N†	P	K	S
Site	inches	pH	%		kg/ha			
Birch Hills	0-30	6.8	3.7	0.3	56	15	1092	386
	30-60	7.7	1.6	0.1	12	1	205	141
Estevan	0-30	8.1	2.1	0.2	72	9	1117	393
	30-60	8.2	1.9	0.2	27	1	232	124
Prince Albert	0-30	6.4	1.6	0.1	44	137	607	27
	30-60	7.3	0.8	0.0	11	12	108	22
Saskatoon	0-30	6.9	2.4	0.3	73	54	1539	191
	30-60	7.5	2.0	0.3	26	10	424	157

* Extractable nutrients

† NH_4^+-N + NO_3^--N

kg/ha, respectively (Table 3). Studies have shown that regardless of soil type, plantation age, or rotation number, the majority of roots in purpose-grown willow plantations are concentrated within the upper 30 cm of soil (Rytter, 1999; Heinsoo et al., 2009). At all sites, except Saskatoon, the average cumulative N uptake by the willow varieties after four years was greater than the measured extractable N amounts (0-30 cm), while the amounts of P, K, and S were sufficient for all sites (Tables 2 and 3). The principal source of additional N taken up by the willow would come from the mineralization of soil organic matter.

During this four-year period, the average annual return of N, P, K, and S to the soil via litterfall was 20, 4, 27, and 6 kg/ha, respectively for all sites combined (Table 4). Litterfall is a primary mechanism for nutrient cycling within most ecosystems (Hughes and Fahey, 1994) and in young woody plants, nutrient storage within the foliage can account for as much as 50% of its nutrient content (Pregitzer et al., 1990). Consequently, depending on the amount of leaf litter biomass and degree of nutrient resorption prior to leaf abscission among different willow varieties, the level of nutrient transfer returning back to soil in leaf litter annually can be large. Notwithstanding these litter additions to the soil each year, the nutrients within fallen leaves are immobilized in the organic material and consequently, are not readily available for plant uptake until being re-mineralized. Mineralization of fallen leaves is controlled by the rate of decomposition and nutrient concentration of the litter (Prescott, 2005) and approximately 30% of willow leaf litter nutrients are re-mineralized and available for plant uptake the following year (Alriksson, 1997). The return of N and P to the soil in litterfall does appear to balance what is removed in stems, so at least in the initial years the soil nutrient reservoir is replenished. This may explain the limited response to nitrogen fertilizer observed in young willow stands (Hangs et al., 2012). However, over several years, the continued removal of nutrient in coppicing will reduce the returns of nutrient to the soil in litterfall in the absence of fertilization.

The expected lifespan of a willow plantation is at least seven rotations (Heller et al., 2003) and due to changes in above- and below-ground growth allocation patterns in later rotations as subsequently more biomass is allocated above-ground once the root system is established (Volk et al., 2004), incremental stem productivity gains up to 130% larger can be expected until the fourth rotation (Larsson, 2001). Based on the results of this study, sustaining high yields of fast-growing willow over multiple rotations on marginal soils with inherently poor fertility (e.g., Prince Albert; Tables 1 and 2), will not be possible without fertilizer amendments, particularly N.

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Table 3. Mean (n = 24) cumulative nutrient content of willow stems (coppiced and harvested material) after four growing seasons at four locations in Saskatchewan.

	N	P	K	S
Site	kg/ha			
Birch Hills	72	11	48	12
Estevan	82	8	61	12
Prince Albert	55	10	39	10
Saskatoon	57	10	46	10

Table 4. Mean (n = 24) cumulative nutrient content of senesced willow leaves after four growing seasons at four locations in Saskatchewan.

	N	P	K	S
Site	kg/ha			
Birch Hills	69	6	44	13
Estevan	74	35	149	23
Prince Albert	66	10	127	29
Saskatoon	114	6	112	33

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