Soil Sci. Soc. Am. J.Accepted paper, posted 03/17/2014. doi:10.2136/sssaj2013.08.0368

Willow Production Systems for Bioenergy Feedstock and C sequestration in Canada and northern U.S.A.: A Review

Beyhan Y. Amichev,* Ryan D. Hangs, Sheala M. Konecsni, Christine N. Stadnyk, Timothy A. Volk, Nicolas Bélanger, Vladimir Vujanovic, Jeff J. Schoenau, Judicaël Moukoumi, and Ken C.J. Van Rees

K.C.J. Van Rees, B.Y. Amichev, R.D. Hangs, S.M. Konecsni, C.N. Stadnyk, V. Vujanovic, and J.J. Schoenau, Centre for Northern Agroforestry and Afforestation, College of Agriculture and Bioresources, University of Saskatchewan, Saskatoon, SK, Canada; T.A. Volk, College of Environmental Science and Forestry, State University of New York, Syracuse, NY, USA; N. Bélanger, Centre d'étude de la forêt, Université du Québec, Montréal, QC, Canada; J. Moukoumi, JM Academic Plus Inc., Sustainability Consulting, Saskatoon, SK, Canada

* Corresponding author (beyhan.amichev@vt.edu).

Abstract

Willow short rotation coppice (SRC) systems are becoming an attractive practice because they are a sustainable system fulfilling multiple ecological objectives with significant environmental benefits. A sustainable supply of bioenergy feedstock can be produced by willow on marginal land using well-adapted or tolerant cultivars. Across Canada and northern U.S.A., there are millions of hectares of available degraded land that have the potential for willow SRC biomass production, with a C sequestration potential capable of offsetting appreciable amount of anthropogenic green-house gas emissions. A fundamental question concerning sustainable SRC willow yields was whether long-term soil productivity is maintained within a multi-rotation SRC system, given the rapid growth rate and associated nutrient exports offsite when harvesting the willow biomass after repeated short rotations. Based on early results from the first willow SRC rotation, it was found willow systems are relatively low nutrient-demanding, with minimal nutrient output other than in harvested biomass.

The overall aim of this manuscript is to summarize the literature and present findings and data from ongoing research trials across Canada and northern U.S.A. examining willow SRC system establishment and viability. The research areas of interest presented here are the crop production of willow SRC systems, above- and below-ground biomass dynamics and the C budget, comprehensive soil-willow system nutrient budget, and soil nutrient amendments (via fertilization) in willow SRC systems. Areas of existing research gaps were also identified for the Canadian context.

Keywords:

Short rotation coppice, SRC willow cultivar biomass yield, carbon (C) sequestration, root development, nutrient budget, fertilization

1. Introduction

Willow (*Salix* spp.) is widespread across Canada's boreal forest and Aspen Parkland ecoregion (Johnson et al., 1995) and, therefore, is the first choice of short rotation coppice (SRC) species to establish in Saskatchewan (Amichev et al., 2011; 2012). Willow shrubs are ideal for SRC systems (Keoleian and Volk, 2005) because they are fast-growing, can easily propagate from cuttings, and have a large amount of easily exploitable genetic diversity that can be used in conventional breeding and molecular biotechnology (Dickmann, 2006). Willow shrubs have the ability to re-sprout after a disturbance, whether through natural breaking, grazing, or human induced coppicing or pruning (Keoleian and Volk, 2005). When used in SRC systems, willows are capable of growing on marginal agricultural land (Labrecque and Teodorescu, 2005) and previously mined regions as reclamation and land utilization tools (Gruenewald et al., 2007).

Verwijst (2001) provided a comprehensive review comparing the genus *Salix* to the genus *Populus*, and comparing willow to poplar cultivation for bioenergy production in order to highlight differences between willow and poplar management with respect to provided services and products. The review paper also addressed the common problems and challenges faced when cultivating willow or poplar, such as species selection and breeding, pest and disease control, and design of production systems (Verwijst, 2001). In short, compared with the genus *Populus*, *Salix* has a much broader genetic base (i.e., approximately ten times larger), more extensive geographical and physiognomic range, and offers a much greater variety of ecosystem services and environmental applications (Verwijst, 2001).

A sustainable supply of fuel wood can be produced by willow on marginal land using well-adapted or tolerant cultivars (Gruenewald et al., 2007). There are approximately 147 Mha of degraded and abandoned agricultural lands within North America potentially available for establishing SRC systems aimed at bioenergy feedstock production (Hoogwijk et al., 2005; Lemus and Lal, 2005). Saskatchewan, one of the prairie provinces of Canada, with > 2 Mha of available degraded land, has the potential for SRC biomass production, with a C sequestration potential capable of offsetting up to 80 % of the annual anthropogenic greenhouse gas emissions in the province (Amichev et al., 2012).

Previous efforts have been made to promote the establishment of willow SRC industry for bioenergy feedstock production. The Salix Consortium is one such effort that was intended to advance willow crops from the experimental trials phase into a commercial business enterprise in the U.S.A., and was based on research from the U.S.A. (Volk et al., 2006), Sweden (Mola-Yudego and Gonzales-Olabaria, 2010), Canada (Mosseler, 1990), and the UK (Armstrong et al., 1999; Bell et al., 2006). Based in New York (U.S.A.), the Salix Consortium (formerly the Empire State Biopower Consortium) was formed in 1995 to facilitate commercialization of willow biomass production in the Northeastern and Midwestern regions of the U.S.A. (Abrahamson et al., 1998; 2002). Similarly, in Canada, governmental programs such as the Agricultural Bioproducts Innovation Program (ABIP) and the Saskatchewan Biofuels Investment Opportunity (SaskBIO) have been developed to promote this industry and encourage extension activities to transfer information between researchers and landowners. Future energy crop production is most likely to occur on marginal agricultural land in order to avoid conflict with food production and compromising food security (Aylott et al., 2010; Volk and Luzadis, 2009). Willow plantations established on marginal lands can decrease fibre demands on existing natural forests and provide a means to recycle organic residues, such as sewage sludge and animal manures (Labrecque and Teodorescu, 2005). For example, there are an estimated 4 Mha of salt-affected abandoned land across the Canadian prairies, approximately 1.6 Mha in Saskatchewan alone, which is unsuitable for arable crop production, but could support SRC production of salt-tolerant willow cultivars (Hangs et al., 2011). Earlier studies have highlighted the ability of willow to grow well on a variety of soil types (Scholz and Ellerbrock, 2002; Stolarski et al.,

Soil Sci. Soc. Am. J.Accepted paper, posted 03/17/2014. doi:10.2136/sssaj2013.08.0368

2011) and the recent work in Saskatchewan by Hangs (2013) was in agreement where first rotation willow SRC yields were >10 Mg ha^{-1} yr^{-1} on sandy soil without fertilization.

In order to produce willow biomass, it is necessary to combine knowledge of both forestry and agronomy practices (Keoleian and Volk, 2005). Throughout the growth cycle of willow SRC systems, intensive management is required in site preparation, planting, weed and pest control, fertilization, coppicing, and harvesting. A fundamental question concerning sustainable SRC willow yields, therefore, is whether long-term soil productivity is maintained within a multi-rotation SRC system, given the rapid growth rate and associated nutrient exports offsite when harvesting the willow biomass after repeated short rotations (i.e., three to five years). A clear understanding of soil nutrient dynamics and soil nutrient budgets during the establishment phase is required to accurately forecast the sustainability of willow SRC systems and the necessity of soil nutrient amendments. For example, fertilization traditionally has been used as a management tool to support the establishment and growth of willow SRC crops; however, its efficacy has been inconsistent (Hangs et al., 2012b; Quaye and Volk, 2013). Other SRC crop establishment factors include the inherent soil fertility at a given site (Mitchell, 1995; Quaye et al., 2011), genotypic variability in nutrient requirements, uptake capacity and/or utilization efficiency (Adegbidi et al., 2001; Weih and Nordh, 2005), genotype x environment interactions (Ballard et al., 2000a; Hofmann-Schielle et al., 1999), previous land use history, suppression of competing vegetation, and mechanical site preparation (Abrahamson et al., 1998; 2002).

The majority of research on willow SRC systems has focused on the above-ground portion of the system, and relatively few studies have been done on the morphological stages of willow fine roots. The processes of fine root production and mortality in a system are difficult to examine due to the high degree of spatial and temporal variability (Norby et al., 2004). However, knowledge about the below-ground portion of willow SRC systems for the climate and soils of a given region, and the dynamics of willow fine roots, in particular, is crucial to understanding the soil-willow interaction with regard to soil C sequestration, nutrient cycling, and long-term sustainability of SRC systems. For example, as a direct result of coppicing in intensively managed willow SRC systems, biomass storage below-ground was increased through encouraging more rapid fine root turnover and contribution to stable soil humus pools (relative to undisturbed woodland sites) which promoted soil C sequestration, e.g., 0.41 Mg C ha^{-1} yr^{-1} and 0.51 Mg C ha^{-1} yr^{-1} to a depth of 23 and 50 cm, respectively (Grogan and Matthews, 2002), as well as increased soil organic matter levels (Zan et al., 2001).

The aim of this manuscript is to summarize the literature and present findings and data from ongoing research trials across Canada and northern U.S.A. examining willow SRC system establishment and viability (Table 1). The research areas of interest presented here are as follows: crop production of willow SRC systems, above- and below-ground biomass dynamics and the C budget, comprehensive nutrient budgets, and nutrient amendments (via fertilization) in willow SRC systems.

[Insert Table 1 here]

2. Crop production of willow SRC systems: an overview

A crucial decision made at the establishment phase of each willow SRC system is site selection. Abrahamson et al. (2002) concluded that shrub willows grow best in loamy soils with a well-developed soil structure and >45cm rooting depth. Although data showed slower initial willow establishment on soils with high clay content, willow growth and productivity in successive rotations was greater in these soils, likely due to much greater nutrient exchange capacity relative to sandy soils (Abrahamson et al., 2002). Similar findings were reported by Ens et al. (2013a) in regard to soil and climate variables affecting willow productivity (*S. purpurea*, "Hotel" cultivar) and nutrition across a broad range of sites in Canada. In general, the greatest yields were observed on sites receiving adequate moisture (especially summer precipitation in first two years) with calcareous medium textured soils (Ens et al., 2013a). The lowest "Hotel" yields were observed on sandy soils, sites with very low precipitation, or a combination of both (Ens et al., 2013a). In addition, it has been suggested that excessively well or poorly drained soils or moderately acidic or alkaline soils (pH <5.5 or >8.0) could also lead to poor willow growth (Abrahamson et al., 2002).

In a SRC system, willows are grown from unrooted cuttings that have been harvested from one-year-old shoots during the dormant winter season (Keoleian and Volk, 2005). The planting density of willow SRC systems is greatly dependant on the entire production system because it affects management decisions, such as weed control and harvest efficiency (Keoleian and Volk, 2005). For willow SRC systems, experimental planting densities of 15,300 plants ha^{-1} (Heller et al., 2004) and 10,000 to 20,000 plants ha^{-1} (Christersson et al., 1993) have been recommended. Higher densities tend to be more efficient at using resources earlier in the rotation, yet have higher establishment costs (Bullard et al., 2002), while lower densities have lower costs, but lead to a delayed peak of mean annual increment (Keoleian and Volk, 2005). A study carried out by Adegbidi et al. (2001) observed the effects of planting density on other components of the production system and found that planting densities, whether 107600, 36960, or 15000 plants ha^{-1} had no significant effect on annual biomass production.

Willow SRC systems are generally harvested on a 3- to 4-yr cycle and are managed using a coppice practice (Keoleian and Volk, 2005). Willows are coppiced (cut to <5 cm tall) after the first growing season during the dormant season (winter) when carbohydrate reserves are at their maximum level in the root tissues (Sennerby-Forsse, 1995). Therefore, coppicing refers to the severing of all aboveground biomass in order to stimulate reinvigoration and accelerate growth toward the theoretical maximum (Sennerby-Forsse, 1995). Coppicing has been found to double the density of willow SRC systems by increasing the number of shoots by 3- to 4-fold (Hytönen, 1995). After 3 to 4 years of growth, harvesting takes place in the dormant season when woody tissue nutrients are translocated to the roots and most foliage nutrients have been deposited on the soil for onsite recycling (Hangs et al., 2013; Lemus and Lal, 2005). Since willow are capable of vigorous re-sprouting after each harvest, 7 to 10 harvests are possible from a single planting resulting in a plantation life span of more than 20 years (Keoleian and Volk, 2005).

One of the many advantages of growing willow as bioenergy feedstock is its large net energy ratio (i.e., high energy output to input ratio). Specifically, at the end of seven three-year harvests, approximately 55 units of harvested bioenergy can be created with 1 unit of fossil fuel input (Keoleian and Volk, 2005) when the farm gate is considered the edge of the system. More recent life cycle analysis that includes haul distances and the uncertainty associated with certain parts of the system has reported energy yields of 18.3 to 43.3 for every 1 unit of fossil fuel invested (Caputo et al., 2013). In any of these studies, the net energy ratio is strongly influenced by yield. Yield, however, was found to be highly dependent on many factors including genetic diversity, soil fertility, climate and crop management (Keoleian and Volk, 2005). Recent work also suggested that many willow cultivars were tolerant of moderately to severely saline soils commonly found in western Canada (Hangs et al., 2011). For example, Hangs et al. (2011) reported sufficient willow growth of a number of willow cultivars developed as bioenergy feedstock under moderately saline conditions (≤5.0 dS/m), and even severe salinity (≤8.0 dS/m). Across the U.S.A. and Canada, weed competition and insufficient soil moisture (Ens et al., 2013a) were identified as the greatest site limitations affecting willow establishment and biomass production in SRC systems, followed by adverse effects by pests (Vujanovic and Labrecque, 2002), although there has been no evidence of pests significantly affecting willow yields (Zalesny et al., 2011). Recently, Corredor et al. (2012; 2014) reported that both host genotype and health status influence the composition of fungal communities in the rhizosphere of willow.

Irrigation has been used to ameliorate moisture regime limitations and was shown to significantly increase willow growth on heavy clay soils (Hangs et al., 2012b). For example, willow yields as high as 27 Mg ha^{-1} yr^{-1} were reported in trials in New York in an irrigated and fertilized plantation (Adegbidi et al., 2001).

3. Above-ground willow biomass growth for C sequestration and bioenergy feedstock production

A willow SRC trial involving 30 willow cultivars was established in Saskatoon, Saskatchewan in order to evaluate the growth and adaptability of willow SRC crops to the soils and climate of the province. A prepared manuscript reporting the first-rotation yields of these 30 willow cultivars is presently in the process of journal peer-review and, therefore, it is referred to as the ’30-cultivar study’ in the current review paper. The 30-cultivar study was established using dormant willow cuttings, each 25 cm long, obtained from the State University of New York - College of Environmental Science and Forestry (SUNY-ESF) which were planted in 2007 at the University of Saskatchewan (Latitude 52.126632; Longitude -106.608294; elevation 510 m above sea level) at Saskatoon, Saskatchewan, Canada. The study site was located in the Elstow Plain ecodistrict of the Moist Mixed Grassland ecoregion within the Prairies ecozone of Saskatchewan (SLC, 2006). The soils at this site are a heavy clay Sutherland Orthic Vertisol (Agriculture Canada, 1998). Mean annual precipitation at this site is 375 mm, mean annual temperature is 2°C, and the average number of frost days is 253 annually (EC-NCD`, 2008). All willow cultivars were planted by hand in spring of 2007 in four separate replications (approximately 7 x 9 m area each) with three double-rows of thirteen plants per row with 1.5 m spacing between double-rows, 0.60 m between rows in a double-row, and 0.60 m between plants within a row, resulting in a planting density of approximately 15,873 plants ha^{-1}. Willow cultivars were coppiced at the end of the first growing season and first-rotation biomass was manually harvested from each plot three years later.

The average first 3-yr-rotation harvested biomass yield in the 30-cultivars study was 10.5 (Oven-dry) Mg ha^{-1} (annual increment = 3.5 Mg ha^{-1} yr^{-1}), ranging from 4.0 to 17.4 Mg ha^{-1} (1.3 to 5.8 Mg ha^{-1} yr^{-1}). These observed yields were similar to other reported willow yields from sites in Saskatchewan (Ens et al., 2013b; Moukoumi et al., 2012) and some sites in the U.S.A. (Kiernan et al., 2003). For example, harvest yields for the SX64 (*Salix miyabeana*) cultivar in the 30-cultivars study, ranging from 9.0 to 12.1 Mg ha^{-1} (3.0 to 4.0 Mg ha^{-1} yr^{-1}) were similar to yield data by Moukoumi et al. (2012) across a range of site quality for three sites near Saskatoon, 1.2 to 15.6 Mg ha^{-1} after 4 years (0.4 to 5.2 Mg ha^{-1} yr^{-1}). Also, the yields of the highest producing cultivars at the Saskatoon site of the 30-cultivars study overlapped the lower end of first rotation willow yields reported by Kiernan et al. (2003) for older cultivars in the U.S.A. (planted between 1993 and 2001), 5.2 to 9.3 Mg ha^{-1} yr^{-1}, but were lower than first rotation yields of new willow genotypes (planted from 2005 to 2007), 6.1 to 12.9 Mg ha^{-1} yr^{-1}, reported by Volk et al. (2011). Based on our findings in the 30-cultivars study, we suggested that the relatively lower yields of some of the cultivars studied in Saskatoon could be due to either herbicide damage (herbicide used for weed control), poor willow root extension due to heavy clay soils, a notable winter dieback of some cultivars, moisture regime limitations during the first rotation (Hangs et al., 2012b), and low plant-available soil N levels (Moukoumi et al., 2012). Our observations from the 30-cultivars study agreed with previous reports that growing degree days (GDD, base 5°C) (Kopp et al., 2001; Moukoumi et al., 2012) was a very important growth limiting factor for willow SRC systems, and the much lower yields observed in the 30-cultivar study adequately corresponded to the lower GDD count at these northern latitudes under Canadian climatic conditions. A similar decrease in willow SRC biomass yield resulting from GDD decrease was previously reported by Kopp et al. (2001) who found that 2.4 to 4.1 % willow yield decreases could occur for each 1 % decrease in GDD. In recent studies in Ontario, Canada, significantly increased willow SRC yields were reported in an agroforestry tree-intercropping system (4.86 Mg ha^{-1} yr^{-1}) compared to a conventional willow SRC system (3.02 Mg ha^{-1} yr^{-1}) due to complementary growth-promoting interactions as influenced by the presence of mature trees (21-yr old mixed tree species) along the willow rows (Cardinael et al., 2012; Clinch et al., 2009).

As part of the 30-cultivars study, and based on the 3PG willow growth modeling work in Amichev et al. (2011), expected first 3-yr rotation yield of SV1 willow SRC systems for all marginal agricultural areas across Saskatchewan averaged 13.6 and 11.8 Mg ha^{-1} (annual increments 4.5 and 3.9 Mg ha^{-1} yr^{-1}) for farm lands in the Prairies and Boreal Plains ecozones of the province, respectively. In the willow yield map of the 30-cultivars study we indicated >4.9 Mg ha^{-1} (1.6 Mg ha^{-1} yr^{-1}) increase of SV1 production, relative to that at the Saskatoon site (9.8 Mg ha^{-1}; annual increment 3.3 Mg ha^{-1} yr^{-1}), on >0.3 Mha of land in Saskatchewan, which emphasized the potential use of this map as a decision-making tool for the bioenergy industry.

Carbon sequestration in willow SRC systems occurs in two distinct forms – the ecosystem and the harvested biomass transferred out of the ecosystem (Amichev et al., 2012). Due to the rapid willow growth and short biomass harvesting rotations, nearly 75% of C removed from the atmosphere and locked within ecosystem components was in dead organic matter (DOM) pools – which included the litter layer, dead fine roots, and soil (Amichev et al., 2012). Even after biomass removal at harvest time, Amichev et al. (2012) projected an increase of DOM C pools at an average rate of 0.9 Mg ha^{-1} yr^{-1}, equivalent to an increase from 205 to 292 Tg C (1 Tg=1 million metric tons) for 2.12 Mha of marginal agricultural land in Saskatchewan, over two full cycles of seven 3-yr willow SRC rotations (i.e., 44-yr simulation period). Their projected C sequestration rates were lower than rates reported in southwestern Quebec for willow SRC systems (1.29 Mg C ha^{-1} yr^{-1}) (including root and soil C stocks), and were approximately equal to the rates for switchgrass (*Panicum virgatum*) SRC systems (1.09 Mg C ha^{-1} yr^{-1}) (Lemus and Lal, 2005).

A much more notable C removal from the atmosphere was projected within the cumulative harvested biomass transferred out of the willow SRC systems every 3 years (Amichev et al., 2012). For example, after two full cycles of seven 3-yr rotations (i.e., 44 years), the average potential C stock in cumulative harvested willow biomass on farm land in the Prairie ecozone of Saskatchewan was 244 Mg C ha^{-1} (rate = 5.5 Mg C ha^{-1} yr^{-1}). This rate was about 20% higher than the average potential C capture in harvested biomass for farm land in the Boreal Plain ecozone of Saskatchewan, 203 Mg C ha^{-1} (rate = 4.6 Mg C ha^{-1} yr^{-1}) (Amichev et al., 2012).

In sum, the total amount of C removed from the atmosphere in two full cycles of seven 3-yr willow SRC rotations in the form of ecosystem C and C in harvested biomass averaged 292 and 215 Mg C ha^{-1} (= 6.6 and 4.9 Mg C ha^{-1} yr^{-1}) in the Prairie and the Boreal Plain ecozones of Saskatchewan, respectively (Amichev et al., 2012). These findings showed that significant amounts of atmospheric CO_2 could be removed by willow SRC systems. Although the C uptake in harvested biomass for willow SRC systems is not a long-term storage of C, the amount of C released to the atmosphere in the process of generating energy from willow feedstock was captured from the atmosphere in the previous 3-5 years, depending on rotation length (Amichev et al., 2012). This short time for willow SRC systems to achieve C neutrality, compared to decades or longer periods for woody biofuels from conventional forest operations, had been recognized to greatly enhance the suitability of willow SRC systems for use to off-set fossil fuels (Amichev et al., 2012).

Due to a lack of other C studies for willow SRC systems in Saskatchewan, Amichev et al. (2012) emphasized the need for additional empirical data, including willow root biomass, soil fertility assessment, woody debris decay, and long-term plant mortality, all of which could be used to improve and validate projected C budget of willow SRC systems in the province. The use of willow SRC systems as a bioenergy crop is promising, but more research from additional trials at different sites was deemed necessary regarding the long-term potential of these systems to sustain a biomass industry in Saskatchewan (Amichev et al., 2012). Additional willow SRC trials across the province would also serve as validation for willow SRC system yield maps, which will be critically important for the next phase of biomass industry development in Saskatchewan - site selection for establishment of bioenergy processing plant facilities.

4. Below-ground willow development: what we know so far

General assumptions and recent data collected across a chronosequence of willow biomass crops indicate that coarse root biomass increases early in the life of the crop, reach a steady mass and remain stable for the remainder of the lifetime of the crop (Pacaldo et al., 2013; Heller et al., 2003), while the temporal dynamics of fine roots are more closely correlated to the surrounding environment (Leuschner et al., 2004). Root turnover studies are particularly difficult due to the simultaneous nature of fine root production and mortality (Rytter, 1999; Rytter and Hansson, 1996). In a method comparison study, including destructive methods, namely soil coring and whole tree excavation (Achat et al., 2008; Rytter, 1999), and non-destructive methods such as the minirhizotron method (Vargas and Allen, 2008) for *in situ* quantification of fine root turnover, Rytter (1999) found that different methods of quantifying fine-root turnover produced various results. Singh et al. (1984) concluded that root system studies and data could be very sensitive to peaks in fine root production and mortality, and that overestimation or underestimation in biomass can result from this temporal variability. Optimal sampling dates for roots determined by the seasonal maxima and minima are, however, difficult to determine (Block, 2004).

Willow fine roots can account for approximately 30 to 50% of annual net primary production (NPP) (Greer et al., 2006; Rytter, 1999) with a ratio of fine roots to above-ground production ranging from 0.4 to 1.2, depending on the environment and year of growth (Rytter, 2001). Willow root systems are characterized by tap and fibrous root arrangements (Puttsepp, 2004).

Brundrett and Kendrick (1990) described the willow root system being comprised of long straight roots bearing shorter, curved roots with root hairs scattered throughout the system. Willow roots typically reach an average depth of 25 to 30 cm during the first growing season, extending into greater depths during the second growing season (Rytter and Hansson, 1996). The rooting depth is primarily responsive to the moisture gradient in the soil profile (Volk et al., 2001) and is relatively deeper when compared to annual crops, such as mustard (*Brassica juncea*), tobacco (*Nicotiana tabacum*) and maize (*Zea mays*) (Keller et al., 2003). This vertical distribution is likely a factor in the high survival rates of willow plantations established on marginal sites because deeper rooting allows for greater accessibility to limited soil resources (Volk et al., 2001). Some of the notable multiple roles of willow root systems include anchorage, nutrient acquisition and storage, and phytoremediation (Corseuil and Moreno, 2001; Jackson et al., 1997; Karrenberg et al., 2003) as well as soil C sequestration (Block et al., 2006; Lemus and Lal, 2005; Zan et al., 2001).

Stadnyk (2010) used three different willow roots measurement and observation methods at several different research trials in Saskatchewan: minirhizotron, sequential soil coring, and whole-tree excavation methods. On average (across all six cultivars), fine root biomass values using the soil coring method ranged from 0.02 to 0.3 Mg ha^{-1} which were considerably smaller than fine root values found using the minirhizotron method, ranging from 0.8 to 7.4 Mg ha^{-1}, while average root biomass value determined using the whole-tree excavation method was 0.5 Mg ha^{-1} (Stadnyk, 2010). Stadnyk (2010) noted that minirhizotron fine root biomass values may be overestimated due to experimental artifacts such as soil-tube interface gaps formed in certain soil types such as Vertisols. In the first growing seasons, monthly fine root NPP was similar across the six willows studied and reached a peak of 3.4±1.8 Mg ha^{-1} (Stadnyk, 2010). These fine root NPP values were similar to that of a hybrid poplar plantation (Gunderson et al., 2008) and were also similar to that of basket willow reported by Rytter (2001) (2.7 to 6.5 Mg ha^{-1} yr^{-1}). However, in other work in the literature, where alternative methods were used for NPP measurement, such as sequential soil cores and ingrowth cores, annual fine root NPP values were lower, ranging from 1.3 Mg ha^{-1} yr^{-1} (Steele et al., 1997) to 2.5 Mg ha^{-1} yr^{-1} (Ostonen et al., 2005) possibly due to the limitations of these methods to account for the simultaneous nature of fine root growth and mortality.

The minirhizotron method also allowed assessment of willow root turnover and longevity. Willow fine root turnover in Saskatchewan ranged from 0.9 to 1.1 yr^{-1} (Stadnyk, 2010) and were similar to values found for a northern hardwood forest, 0.7 to 2.0 yr^{-1} (Burke and Raynal, 1994), and for a mixed stand, 0.45 to 2.19 yr^{-1} (Nadelhoffer et al., 1985). However, fine root turnover values from another willow SRC system studied in Sweden by Rytter and Rytter (1998) were much higher, 4.9 to 5.8 yr^{-1}. These higher values were suggested by the authors to be due to reduction of water and nutrient restrictions in fast growing plantations (Rytter and Rytter, 1998).

Stadnyk (2010) also carried out whole tree extractions to examine the coarse root structure and relative biomass of the entire two-year-old plant within a 1-m radius from the cutting to a depth of approximately 30 cm. On average (across six cultivars), total root biomass ranged from 0.5 to 1.0 Mg ha^{-1}, with lateral root systems reaching up to 128 cm from the cutting (Stadnyk, 2010). Similar root biomass data were reported from an irrigated willow potted trial in Quebec (0.6 Mg ha^{-1}) (Guidi and Labrecque, 2010). Willow biomass crop root systems that were excavated to a depth of 45 cm across a chronosequence ranging from 5 to 19 years old showed that standing below-ground biomass, including coarse and fine roots and below-ground stool, was about 14.1 Mg ha^{-1} at age 5 and reached 31.4 Mg ha^{-1} at age 14 and remained unchanged at age 19 (Pacaldo et al., 2013). The root: shoot ratio for all cultivars studied by Stadnyk (2010) ranged from 0.09 to 0.51, which was similar to values found in a hybrid poplar system in India (0.12 to 0.31) (Swamy et al., 2006), and was similar to values in an irrigated willow potted trial (0.54) (Guidi and Labrecque, 2010).

The contribution of the roots to the soil CO_2 efflux is proportional to fine root production (Norby et al., 2002). As the roots senesce, the less recalcitrant portions decompose and are incorporated into soil organic matter, the rates of which are dependent on factors such as climate, edaphic conditions and fine root diameter (Puttsepp, 2004). It is well understood that SRC systems in the initial years following establishment sequester less carbon if the mineralization rate is initially high, or even experience C loss due to tillage and site preparation practices (Ens et al., 2013b; Girouard et al., 1999; Hansen, 1993). One growing season after coppicing, the estimated fine root C content of willow in Saskatchewan ranged from 0.1 to 0.4 Mg C ha^{-1} (Stadnyk, 2010) which were much smaller than those found by Zan et al. (2001), 2.3 Mg C ha^{-1}, in a 4-yr-old willow SRC system in southwestern Quebec. In Ontario, Canada, Cardinael et al. (2012) reported increased below-ground C pools (1.5 Mg C ha^{-1}, relative to a control, 1.3 Mg C ha^{-1}) in an agroforestry, tree-intercropping willow production system which promoted significant increase (from baseline levels) of soil organic carbon by 48 % (during the first willow rotation) relative to a conventional willow SRC system where soil organic carbon increased by 27 %. In Pacaldo et al. (2013) chronosequence study standing fine root biomass ranged from 5.6 Mg ha^{-1} at age five to a 6.7 Mg ha^{-1} at age 19, and at one site located on different soils in a 14-year-old willow stand, the standing fine root biomass was 9.9 Mg ha^{-1}. The differences in stand age and site conditions among the studies, among other factors, could explain the differences in fine root C stocks.

The present understanding about root distribution in the soil profile is that the majority of willow roots grow close to the surface and substantially decrease with soil depth (Hendrick and Pregitzer, 1996; Kummerow et al., 1990). However, findings from other studies diverge from this current understanding indicating an increase, then a decrease in root density with depth (Liedgens and Richner, 2001; Nicoullaud et al., 1994). This pattern was also observed in the first growing season (post-coppice) for the willow cultivars Canastota *(Salix sachalinensis* x *miyabeana, cultivar ID 9970-036)* and Sherburne *(S. sachalinensis* x *miyabeana, cultivar ID 9871-31)*, and in the second growing season (post-coppice) for willow cultivars Canastota, Sherburne, Fish Creek *(S. purpurea, cultivar ID 9882-34)*, and Allegany (S. purpurea, cultivar ID 99239-015)) in Saskatchewan (Stadnyk, 2010). Stadnyk (2010) reported a significant increase of fine root biomass at all depths from 2008 to 2009, although there was no clear relationship between fine root biomass and soil depth for any of the cultivars; the highest fine root biomass was observed at 10-20 cm depth averaging 2.6 Mg ha^{-1} in the first growing season.

Fine root systems under short rotation willow coppice appeared to be more responsive to edaphic controls on the plant system than to inherent biological characteristics of the species (Stadnyk, 2010). In assessing the influence of soil type on early root growth habits of willow , it was observed that the sandy soils provided better growth environments for willow roots than soils of high clay content. In areas of insufficient moisture, such as the semi-arid prairie conditions, roots were likely to extend laterally and vertically to locate sources of water (Stadnyk, 2010). However, dry, fine textured soils provided mechanical restrictions to root growth, which was not a concern in coarse textured soils. It is suspected that the lack of soil moisture at some sites had a substantial effect on willow fine root growth, but further studies are needed in this regard (Stadnyk, 2010). This is particularly true in prairie landscapes where a shallow groundwater table can supply adequate amounts of moisture for growth, which can compensate for low precipitation and a low soil water-holding capacity.

5. Comprehensive nutrient budget of willow SRC systems

Willows have the natural ability to cycle available soil nutrients internally and externally aiding their long-term growth (Ericsson, 1994; Hangs et al., 2013). First, willows have the ability to store temporarily in their perennial woody components (i.e., coarse roots, above- and below-ground stool) large amounts of nutrients (Ericsson, 1994) in the form of N compounds, starch, sugars, fats and hemicellulose (Bollmark et al., 1999). This internal cycling of nutrients within high-yielding willow plantations was recognized as a natural means to limit nutrient export offsite and to decrease fertilizer requirements, thus reducing the overall production costs of the system (Ericsson, 1994). A second important nutrient cycle that has been noted in willow SRC systems occurs externally at the leaf litter-soil interface. Approximately one-third of the total nutrient demand could be met by mineralization of leaf litter in established bioenergy plantations (Ericsson, 1994). The nutrient supply released from leaf litter was found to depend on biotic and abiotic factors, such as pH, temperature, soil moisture, N:lignin ratio and microbial activity (Ericsson, 1994). Bollmark et al. (1999) observed that the amount of N lost from senescing leaves directly corresponded to increase of N in perennial organs, such as roots and shoots, thus helping close the nutrient cycling loop once the leaves decompose and the nutrients become plant available.

Nutrient budget studies in willow SRC systems are available in the literature (Alriksson, 1997; Ericsson, 1984; Hytönen, 1996); however, there was no work available that studied comprehensively the nutrient budget of willow SRC systems that included nutrient inputs, outputs, and transfers. Therefore, in order to develop reliable nutrient budgets for SRC willow production in Saskatchewan, trials of several willow cultivars were established at different sites across a 500 km north-south pedo-climatic gradient (Hangs, 2013). Hangs (2013) quantified comprehensively the nutrient budget of nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), and magnesium (Mg) for the first 3-yr rotation of coppiced willow SRC systems (i.e. initial 4-yr period). The above- and below-ground nutrient pools that were accounted for by Hangs (2013) included: nutrient flux into the system (e.g., atmospheric deposition and soil mineral weathering), out of the system (e.g., coppiced and harvested biomass, and leaching) and nutrient transfers within the soil-willow system, which are neither input nor output into/from the system (Fig. 1, 2, and 3). For the purposes of the current paper, the transfer pools were further divided into two general groups in regard to expected time of nutrient release from these pools back into the soil-willow system: (i) ephemeral transfer pools that include canopy exchange and soil organic matter mineralization, and (ii) perennial transfer pools that include leaf litter, dead fine roots, stool, standing fine and coarse root biomass, and leaf biomass (Fig. 1, 2, and 3).

Across all study sites, the average initial pre-planting soil extractable cumulative nutrient pool was 25,145 Kg ha^{-1}, with the lowest stocks represented by N (<1%; 80 Kg ha^{-1}) and P (<1%; 66 Kg ha^{-1}), followed by S (2%, 579 Kg ha^{-1}), K (5%, 1,322 Kg ha^{-1}), Mg (18%, 4,574 Kg ha^{-1}) and dominated by Ca (74%, 18,524 Kg ha^{-1}) (Fig. 1, 2, and 3), which is typical of the calcareous prairie soils within western Canada (Hangs, 2013). On average, approximately 1.6% of initial cumulative soil nutrients, equal to 393 kg ha^{-1}, were removed from the willow SRC system during the initial four years via harvesting (266 kg ha^{-1}), leaching (105 kg ha^{-1}), and coppicing (22 kg ha^{-1}) events (Fig. 1, 2, and 3). Nutrient removal ranged from 1% (Ca, and Mg) to 91% (N) relative to initial levels of the individual soil nutrients (Fig. 1, 2, and 3). However, this nutrient removal off-site, at the whole soil-willow system scale, was countered in full, partially by nutrient release from ephemeral nutrient transfer pools (=309 Kg ha^{-1} or 1.2% relative to initial cumulative levels) mainly via organic matter mineralization (292 kg ha^{-1}), and partially by nutrients added into the system from input sources, i.e., atmospheric deposition and soil mineral weathering (=218 Kg ha^{-1} or 0.9% relative to initial cumulative levels) (Fig. 1, 2, and 3). Nutrient release within the soil-willow system from ephemeral transfer pools ranged from 0% (Ca, Mg) to 228% (N), and nutrient additions from input sources ranged from <1% (Ca, Mg) to 28% (N) relative to initial levels of individual soil nutrients (Fig. 1, 2, and 3).

[Insert Fig. 1 here]

[Insert Fig. 2 here]

[Insert Fig. 3 here]

As a result, the average net nutrient levels for the initial 4-yr nutrient budget of the whole soil-willow system in Saskatchewan (to be clearly distinguished from plant available nutrient budget) was a surplus of 0.5% relative to initial cumulative soil nutrient levels. This cumulative nutrient budget change accounted for six nutrients presented in Fig. 1, 2, and 3 and was estimated using Eq. 1. as follows: $0.5\% = 100*(218 + 309 – 393 \text{ Kg ha}^{-1})/25{,}145 \text{ Kg ha}^{-1}$. Calculating a whole soil-willow system nutrient budget separately for individual nutrients revealed that half were in surplus (165% for N, <1% for K, 19.2% for S) and half were in negligible deficit (<1% for P, Ca, Mg) at the end of the 4-yr period (Fig. 1, 2, and 3). Individual nutrient budget change was also estimated using Eq. 1. For example, N nutrient budget change was estimated as 165% = 100*(23 + 181 – 72 Kg ha^{-1})/80 Kg ha^{-1} (Fig. 1, 2, and 3)

$$Nutrient\ budget\ change\ (\%) = \frac{\sum_{i=1}^{n}(Input_i + Ephemeral_i - \ Output_i)}{\sum_{i=1}^{n}(Initial_i)} * 100 \qquad \text{Eq.1}$$

Where i (1 to n) = soil nutrient; $n = 6$ (N, P, K, S, Ca, and Mg) for the estimation of cumulative nutrient budget change (%), and $n = 1$ (i.e., individual nutrient) for the estimation of nutrient budget change (%) of an individual nutrient; $Input_i$ = additions of nutrient i into the soil-willow system via atmospheric deposition and soil mineral weathering; $Ephemeral_i$ = release of nutrient i into the soil-willow system from ephemeral transfer pools (canopy exchange and organic matter mineralization); $Output_i$ = removal of nutrient i from the soil-willow system via harvesting, leaching or coppicing; $Initial_i$ = pre-planting initial stocks of nutrient i within the soil-willow system.

Approximately 2.4% relative to initial cumulative nutrient levels, equal to 611 Kg ha^{-1}, were taken up by willow plants and stored in the form of foliage, stool, fine and coarse root biomass during the initial 4-yr period of willow SRC systems in Saskatchewan (i.e. perennial transfer pools; Fig. 1, 2, and 3). The nutrients in these pools would persist from one rotation to the next and remain onsite for a total of seven 3-yr rotations and, therefore, for the purposes of this paper, they were considered neither nutrient input nor output into/from the whole soil-willow system (Fig. 1, 2, and 3). The nutrient budget in our present paper focused solely on the short-term (4-

yr) initial period of willow SRC establishment and accounted for all processes in regard to nutrient input, output and short-term transfer (ephemeral pools within the system) (Fig. 1, 2, and 3). The nutrient storage and release into/from perennial transfer pools were not included in the estimation of percent nutrient budget flux for the whole soil-willow system as these pools largely influence the long-term nutrient availability on the site, which was beyond the scope of the present paper.

Hangs (2013) presented alternative agronomic nutrient budget estimation in willow SRC systems that calculated net changes in plant available nutrient levels, which are more conducive to fertility management practices suited to farmers, as opposed to the whole soil-willow system we employed. In the nutrient budget estimation Hangs (2013) treated foliage, stool, fine and coarse root biomass pools as nutrient outputs from the plant available nutrient stocks, while they were assigned in perennial transfer pools within the soil-willow system in our present paper and were not included in the nutrient budget change (Eq.1). Due to this different approach, Hangs (2013) estimated negative change in plant available N (-24%), K (-9%), Ca (-2%) and Mg (-2%) levels and positive change in plant available P (105%) and S (17%) levels after an initial four year period relative to initial soil nutrient levels.

A similar study which we have done also showed negative plant available N nutrient change and significant nutrient loss during the initial establishment years for willow grown on former agricultural fields in central Saskatchewan, Canada. The three willow (*S. miyabeana* Seemen (SX64)) plantations (Harris and Saskatoon 1 and 2) were intercropped with caragana (*Caragana arborescens*) at different levels of intensity [i.e. monoculture of willow (W), monoculture of caragana (C), mixing with a 2:1 willow:caragana ratio (2W:1C), mixing with a 2:1 willow:caragana ratio with irrigation (2W:1W-irr), and mixing with a 1:1 willow:caragana ratio

(1W:1C)]. Plantations were established (late May) in a randomized complete block design using 25 cm willow cuttings and 80 cm caragana whips (see Moukoumi et al. (2012) for a full description of the sites and experimental design). In order to limit soil disturbance, weed control was done by hand every two weeks from May to September 2007 and 2008. Three soil samples per plot were collected at the end of the first and second growing seasons (late September to early October 2007 and 2008) at a depth of 0–10 cm. The samples were air-dried at room temperature and then aggregates were gently broken down with a rolling pin to pass through a 2-mm mesh. Soil mineral N, i.e. NO_3^- and NH_4^+, was extracted with a 2 N KCl solution (Maynard et al., 2007). Nitrate and NH_4^+ concentrations in the extracts were measured colorimetrically with a Technicon Autoanalyzer.

Soil available N was mainly in the NO_3^- form and mineral N levels were higher for the Harris and Saskatoon 1 site compared to Saskatoon 2 and generally declined between the end of the first and second growing seasons (Table 2). The decrease was statistically significantly at all sites when all treatments were combined; however, for willow monoculture plots, the only significant decrease was at Saskatoon 1 where the dry matter production was the highest (Moukoumi et al., 2012). Willow stem height and diameter, crown dimension and dry matter production declined from the N-rich to the N-poor site as follows: Saskatoon 1>Harris>Saskatoon 2. The proportional decrease in soil available N was reversed: Saskatoon 2>Harris>Saskatoon 1, which suggests that the potential for soil mineral N depletion is greater on more productive soils with greater initial N availability. Similarly, Ens et al. (2013b) also reported an average soil [NO_3^- + NH_4^+]-N reduction of 3.1 and 2.6 mg kg^{-1} for 0-20 cm and 20-40 cm soil depths, respectively, in the initial three year period of nine short-rotation willow trial sites of *S. purpurea* (“Hotel” cultivar) established on a variety of soil types across Canada. The sites that responded the most, at least for NO_3^- at the 0-20 cm depth, were also sites which appeared to have higher initial soil available N and biomass yields. This general pattern of N impoverishment indicates that the rate of uptake of N by willow exceeds the maximum rate of N mineralization. Unlike the two previous studies, however, Ens et al. (2013b) estimated soil nutrient change using a retrospective analysis approach by sampling the soil from adjacent reference plots to use as a surrogate source for the expected initial pre-planting soil nutrient levels at the willow trial sites. Also, in comparison to Hangs (2013), the willow stands studied in Ens et al. (2013b) were not coppiced in year 1.

Nutrient uptake by willow plants is partially countered by nutrient release from decomposing litter components within the whole soil-willow system. The average input to plant available soil nutrient pool from decomposing leaf and fine root litter during the initial rotation in Saskatchewan was 71, 16, 66, 22, 127 and 30 kg ha^{-1} of N, P, K, S, Ca and Mg, respectively (Fig. 1, 2, and 3) (Hangs, 2013). The majority of the N (70 %), P (76 %), and S (53 %) contribution came from fine root turnover, while leaf litter supplied the majority of K (73 %), Ca (88 %), and Mg (61 %) (Hangs, 2013). Willow leaves in SRC systems in Saskatchewan, accounting for less than a third of the above-ground biomass, were the largest above-ground sink of soil nutrients, containing about 69, 63, 72, 72, 64, and 69 % of the total amount of N, P, K, S, Ca and Mg, respectively, stored in above-ground biomass (Hangs, 2013). These findings supported the current understanding that, in the long-term, nutrient cycling from leaf litter decomposition and fine root turnover are very important natural mechanisms that help to satisfy the nutritional demands of SRC willow plantations (Christersson, 1986; Ericsson, 1994; Ingestad and Ågren, 1984; Rytter, 2001).

[Insert Table 2 here]

Another long-term nutrient storage pool in willow SRC systems is the below-ground plant material. The nutrient status estimates of willow stool, fine and coarse root tissues in SRC systems in Saskatchewan (Hangs, 2013) were within the range of values reported in the literature (Pacaldo et al., 2011; Puttsepp et al., 2007; Rytter, 2012; Zan et al., 2001). The majority of N, P, and S were stored in the below-ground biomass, while the majority of K, Ca, and Mg were in the above-ground biomass, primarily the leaf litter (Fig. 1, 2, and 3) (Hangs, 2013). The bulk of both biomass (84 %) and nutrient content (95 %) dedicated to below-ground tissue were associated with fine roots (Hangs, 2013). Even in older willow biomass crops the standing fine root biomass made up 47 to 67% of the total below-ground biomass (Pacaldo et al., 2013), which highlights the relative importance of the fine root fraction in SRC willow production systems (Rytter, 2012).

In general, willow can be successfully grown with much less soil nutrient uptake relative to other biomass energy crops (e.g. miscanthus (*Miscanthus x giganteus*), switchgrass, etc.) (Boehmel et al., 2008; Kering et al., 2012; Weih et al., 2011). The annual nutrient removals via harvestable biomass in the first 3-yr rotation of coppiced willow SRC systems of six willow cultivars were 13 to 20, 2 to 3, 10 to 15, 2 to 3, 23 to 43, and 3 to 6 Kg ha^{-1} yr^{-1} for N, P, K, S, Ca, and Mg, respectively (Hangs, 2013). Although the soil nutrient demands differ among willow cultivars (Tharakan et al., 2005; Weih and Nordh, 2002), an obvious reason for the better nutrient use efficiency of willow SRC systems could be the fact that willow foliage, and the nutrients contained in senescent leaves, stayed on site and were re-used by the willow. Unlike the removals of all above-ground biomass in perennial herbaceous bioenergy plantations such as miscanthus and switchgrass, the SRC willow plantations cycled >7 Mg of leaf litter biomass prior to harvest (Hangs, 2013), which would influence long-term nutrient cycling and increase soil organic matter levels (Lal, 2009). This capacity of leaf litter N cycling in willow SRC systems has been recognized previously in regard to meeting nutrient demands in subsequent rotations (Christersson, 1986; Ericsson, 1994). However, despite the efficient internal and external nutrient cycle within willow SRC systems, fertilizer application was recommended to compensate for long-term nutrient losses from harvesting willow stems (Abrahamson et al., 2002; Ericsson, 1994), which would equate to approximately 25 kg N ha^{-1} yr^{-1} with current production levels observed in Saskatchewan (Hangs, 2013).

6. Nutrient amendments for willow SRC systems

Producing and maintaining yields in willow SRC systems requires an adequate supply of nutrients (Adegbidi et al., 2003). Similar to the observations by Ens et al. (2013b), Kowalik and Randerson (1994) reported that the major limiting factor to biomass production in willow SRC systems was N availability; therefore, fertilization was recommended to maintain growth rates over many rotations (Lemus and Lal, 2005). Despite the extensive research on fertilizer use in SRC systems, the optimal time to apply fertilizer is still unknown for SRC systems in North America. Previous research has examined the effects of fertilizer application after the first three-year harvest cycle (Christersson, 1987), for four consecutive years following planting (Alriksson et al., 1997), annually for up to nine years following planting (Adegbidi et al., 2001), prior to planting and six years following planting (Gruenewald et al., 2007), and most commonly in the growing season following coppicing, which is the second growing season (Adegbidi and Briggs, 2003; Adegbidi et al., 2003; Ballard et al., 2000b; Hytönen and Kaunisto, 1999).

A recent study conducted under Canadian conditions studied N fertilization recovery and the effects of fertilization in the year of planting for willow SRC systems (Konecsni, 2010). Konecsni (2010) examined the effects of first year N fertilization on biomass production of five willow cultivars in two different ecozones in Saskatchewan. Differences in soil type at the two sites resulted in more significant differences in willow yields compared to yield response to fertilizer treatments (Konecsni, 2010). For example, tree heights, soil NO_3-N and foliar-P were all found to be significantly greater on one of the sites while the number of shoots per tree, biomass yield, soil PO_4^- and foliar-N and N:P ratios were significantly greater on the other site (Konecsni, 2010). The single application of N fertilizer in the first year did not have any positive or negative effects on willow growth in these SRC systems; biomass was 0.6 to 1.2 and 0.7 to 0.9 Mg ha^{-1} for fertilized and control plots, respectively (Konecsni, 2010). Similar lack of willow yield response to N additions or organic amendments were also reported by Quaye and Volk (2013). However, there were single isolated cases where foliar N and shoot diameter differed significantly between fertilizer treatments (Konecsni, 2010). The majority of N recovered by the willow was accumulated in the leaf components, although such recovery was very low among all cultivars (Konecsni, 2010). Only a negligible fraction of the applied N (0.3 to 4.8%) was recovered by the foliar tissue and this poor fertilizer recovery may explain the lack of fertilizer response in their study (Konecsni, 2010). Booth (2008) reported similar findings in northern Saskatchewan, where recovery of N fertilization in the year of planting was 0.8 to 2.5% by poplar (*Populus spp.*) leaves.

The findings by Konecsni (2010) suggested that in the year of planting, willow SRC system management should be directed to ensure high plant survival, such as applying weed control, while in the second year after planting, the focus could be shifted to fertilizer application to ensure optimal willow growth of the post-coppiced willow plants with well-developed root systems. For example, fertilizers applied in the year after coppicing increased biomass production of willow SRC systems by 8 to 134 %, 7 to 75 % and 9 to 39 % over control treatments in years one, two, and three, respectively (Adegbidi et al., 2003). Although the ability of irrigation to increase willow biomass yield in semi-arid Saskatchewan was expected, Hangs et al. (2012b) reported that irrigation also increased fertilizer use efficiency. In other studies elsewhere, fertilizer applications, whether using organic or inorganic fertilizers, have also been reported to significantly increase the biomass production of bioenergy SRC systems (Adegbidi et al., 2001; Arevalo et al., 2005; Ballard et al., 2000b; Christersson, 2006; Ferm et al., 1989; Gruenewald et al., 2007; Hytönen and Kaunisto, 1999). Most recently, studies in the U.S.A. (Quaye and Volk, 2013) and Canada (Cardinael et al., 2012) for first rotation willow production showed that, depending on the nutrient status of the sites, willow biomass can be produced without fertilizer additions, most likely due to the high internal nutrient cycling in willow SRC systems.

There are a great number of fertilizers available for use in willow SRC systems. Types of fertilizers that have been already studied included green manure (Arevalo et al., 2005), anaerobically digested sewage sludge, composted poultry manure, composted sewage sludge (Adegbidi and Briggs, 2003), waste water and landfill leachates (Hasselgren, 1998), slow-release inorganic fertilizers (Adegbidi et al., 2003), and ash by-products (Hytönen and Kaunisto, 1999). Slow-release fertilizers can both minimize leaching losses and maximize fertilizer effects, but they are often quite expensive (Adegbidi et al., 2003) and immense amounts of energy were consumed in their production accounting for 20-30 % of total bioenergy production costs (Hasselgren, 1998). Fertilization with biosolids, such as sewage sludge and animal manure, was favourable with SRC systems because it was a non-food crop, which decreased the risk of disease transmission to humans (Keoleian and Volk, 2005). Biosolids were also an attractive fertilizer option because they were energy-efficient, contained P and K that could also be utilized by willow, and were much more cost-efficient relative to synthetic fertilizers (Heller et al., 2003). However, the application of biosolids as fertilizers could also raise environmental concerns because excess application of biosolids, exceeding the willow's uptake capacity for N and P, could lead to contamination of surface and groundwater (Adegbidi and Briggs, 2003). Ash by-product from the burning of biomass during bioenergy conversion (through gasification) had also been used as a soil amendment to supply nutrients (Hytönen and Kaunisto, 1999). The use of ash by-products as a soil amendment could provide a unique opportunity to create a nutrient circling loop in which a portion of the soil nutrients transported offsite in the woody components of willow SRC systems are recycled to the soil to foster future willow growth.

7. Concluding remarks

Willow SRC systems are becoming an attractive practice because they are a sustainable system fulfilling multiple ecological objectives with significant environmental benefits (Rockwood et al., 2004). Willow plantations can remain productive for approximately 20 to 30 years (Abrahamson et al., 1998; Heller et al., 2003) with removal of biomass occurring approximately seven times in 3- to 4-yr rotations (Keoleian and Volk, 2005). Willow SRC have the capability to increase site (Keoleian and Volk, 2005) and soil quality (Lemus and Lal, 2005) when planted on agricultural land. When compared to annual cropping systems, SRC can increase soil porosity, infiltration, preferential flow and hydraulic conductivity in clayey soils (Mele et al., 2003). In order to satisfy plant nutritional requirements, the deep perennial rooting systems of woody species are capable of absorbing cations and other trace elements that are inaccessible to shallow annual root systems. The absorbed nutrients are returned to the soil surface through litterfall, thereby enhancing nutrient cycling of the site (Mele et al., 2003).

Willow SRC systems can provide many benefits to farmers, the most obvious being additional cash flow from bioenergy feedstock production, especially when grown on marginal land unsuitable for annual food crop production. However, a more comprehensive assessment of the value of willow SRC systems should take into consideration non-monetary benefits as well, such as increased biodiversity, C sequestration, quality of seepage water and aesthetic values (Gruenewald et al., 2007). For example, it is well-established that willow SRC systems can play a significant role in reducing atmospheric CO_2 levels by sequestering C for long-term storage in their extensive root systems (Sanchez et al., 2007; Smith, 1995), as well as producing feedstock as fossil fuel substitutes for energy production (Amichev et al., 2012).

Despite the decades-long study of willow SRC systems in Europe and North America, there are still research gaps that must be addressed. Comprehensive life cycle assessment of willow SRC systems has not been completed in Canada, especially within the semi-arid temperate regions, yet they are crucially important in understanding the environmental and socio-economic benefits of willow crop establishment. Furthermore, with the relatively new establishment of willow plantations in Saskatchewan, obtaining accurate below-ground C sequestration values is important in the development and validation of C budget models for SRC systems comprised of different willow cultivars. Specifically, fine roots are often a focal point of below-ground C sequestration as they represent approximately 60% of total willow root C (Grigal and Berguson, 1997; Hangs et al., 2012a; Zan et al., 2001). Additionally, maintaining currently established willow trials in Saskatchewan should become a priority, as these sites would continue providing necessary data in regard to expected willow yields, nutrient budget flux, C flux, and overall site sustainability in each consecutive rotation.

Establishing willow SRC systems in Saskatchewan for bioenergy feedstock production is advantageous for renewable energy considerations, and a fundamental question that has to be answered is the sustainability of willow production over multiple rotations. Based on early results from an initial four-year rotation in Saskatchewan (Hangs, 2013), it was found that willow SRC systems were relatively low nutrient-demanding, with minimal nutrient output other than in harvested biomass. However, even with very efficient nutrient cycling in the initial 4-yr period, we would expect future deficits of plant available soil nutrients to occur, in particular N and P, without nutrient amendments. Over the course of multiple rotations, continuing nutrient uptake within tree biomass and repeated harvesting will likely necessitate fertilization to ensure sufficient site nutrient supply. Nutrient amendments in willow SRC systems would maintain long-term soil fertility, thus helping advance purpose-grown willow biomass energy crops as a viable alternative in Canada’s bioenergy sector.

Acknowledgements

The authors would like to thank the Saskatchewan Ministry of Agriculture, NSERC Strategic Grants Program, and the International Plant Nutrition Institute for funding. Much appreciation also goes to B. Brewster, G. Harrison (Pacific Regeneration Technologies), and S. Heidinger (SaskPower) for providing the field sites, and to D. Jackson and all summer students, colleagues, and family who helped with any field and laboratory work.

References

Abrahamson, L.P., D.J. Robison, T.A. Volk, E.H. White, E.F. Neuhauser, W.H. Benjamin, and J.M. Peterson. 1998. Sustainability and environmental issues associated with willow bioenergy development in New York (U.S.A.). Biomass Bioenergy 15:17-22.

Abrahamson, L.P., T.A. Volk, R.F. Kopp, E.H. White, and J.L. Ballard. 2002. Willow biomass producer's handbook, SUNY-ESF, Syracuse, NY.

Achat, D., M. Bakker, and P. Trichet. 2008. Rooting patterns and fine root biomass of *Pinus pinaster* assessed by trench wall and core methods. J. For. Res. 13:165-175.

Adegbidi, H.G., and R.D. Briggs. 2003. Nitrogen mineralization of sewage sludge and composted poultry manure applied to willow in a greenhouse experiment. Biomass Bioenergy 25:665-673.

Adegbidi, H.G., R.D. Briggs, T.A. Volk, E.H. White, and L.P. Abrahamson. 2003. Effect of organic amendments and slow-release nitrogen fertilizer on willow biomass production and soil chemical characteristics. Biomass Bioenergy 25:389-398.

Adegbidi, H.G., T.A. Volk, E.H. White, L.P. Abrahamson, R.D. Briggs, and D.H. Bickelhaupt. 2001. Biomass and nutrient removal by willow clones in experimental bioenergy plantations in New York State. Biomass Bioenergy 20 (6):399-411.

Agriculture Canada. 1998. The Canadian system of soil classification, Third edition Soil Classification Working Group, Agriculture and Agri-Food Canada, Publication 1646.

Alriksson, B. 1997. Influence of site factors on *Salix* growth with emphasis on nitrogen response under different soil conditions. Dissertation, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Alriksson, B., S. Ledin, and P. Seeger. 1997. Effect of nitrogen fertilization on growth in a *Salix viminalis* stand using a response surface experimental design. Scand. J. Forest Res. 12:321-327.

Amichev, B.Y., R.D. Hangs, and K.C.J. Van Rees. 2011. A novel approach to simulate growth of multi-stem willow in bioenergy production systems using a simple process-based model (3PG). Biomass Bioenergy 35:473-488.

Amichev, B.Y., W.A. Kurz, C. Smyth, and K.C.J. Van Rees. 2012. The carbon implications of large-scale afforestation of agriculturally marginal land with short-rotation willow in Saskatchewan. Glob. Change Biol. Bioen. 4 (1):70-87.

Arevalo, C.B.M., A.P. Drew, and T.A. Volk. 2005. The effect of common Dutch white clover (*Trifolium repens L.*), as a green manure, on biomass production, allometric growth and foliar nitrogen of two willow clones. Biomass Bioenergy 29:22-31.

Armstrong, A., C. Johns, and I. Tubby. 1999. Effects of spacing and cutting cycle on the yield of poplar grown as an energy crop. Biomass Bioenergy 17:305-314.

Aylott, M.J., E. Casella, K. Farrall, and G. Taylor. 2010. Estimating the supply of biomass from short-rotation coppice in England, given social, economic and environmental constraints to land availability. Biofuels 1:719-727.

Ballard, B.D., R.D. Briggs, T.A. Volk, L.P. Abrahamson, and E.H. White. 2000a. Effect of slow-release nitrogen fertilization on aboveground biomass production of five *Salix* clones and one *Populus* clone in a short-rotation-intensive-culture (SRIC) bioenergy plantation. Short-Rotation Woody Crops Program at SUNY-ESF, Syracuse, NY.

Ballard, B.D., R.D. Briggs, T.A. Volk, L.P. Abrahamson, and E.H. White. 2000b. Biomass power for rural development technical report: effect of slow-release nitrogen fertilization on aboveground biomass production of five *Salix* clones and one *Populus* clone in a short-rotation intensive culture (SRIC) bioenergy plantation. United States Department of Energy, Nigra Mohawk Power Corporation, Syracuse, NY.

Bell, A.C., S. Clawson, and S. Watson. 2006. The long-term effect of partial defoliation on the yield of short-rotation coppice willow. Ann. Appl. Biol. 148:97-103.

Block, R. 2004. Fine root dynamics and carbon sequestration in juvenile hybrid poplar plantations in Saskatchewan, Canada. M.Sc. thesis. Univ. of Saskatchewan, Saskatoon, Canada.

Block, R., K. Van Rees, and J. Knight. 2006. A review of fine root dynamics in *Populus* plantations. Agroforest. Syst. 67:73-84.

Boehmel, C., I. Lewandowski, and W. Claupein. 2008. Comparing annual and perennial energy cropping systems with different management intensities. Agric. Syst. 96 (1-3):224-236.

Bollmark, L., L. Sennerby-Forsse, and T. Ericsson. 1999. Seasonal dynamics and effects of nitrogen supply rate on nitrogen and carbohydrate reserves in cutting-derived *Salix viminalis* plants. Can. J. For. Res. 29:85-94.

Booth, N.W.H. 2008. Nitrogen fertilization of hybrid poplar plantations in Saskatchewan, Canada. M.Sc. Thesis, University of Saskatchewan, Saskatoon, SK.

Brundrett, M.C., and W.B. Kendrick. 1990. The roots and mycorrhizae of herbaceous woodland plants. II. Structural aspects of morphology. New Phytol. 114:469-479.

Bullard, M.J., S.J. Mustill, S.D. McMillan, P.M.I. Nixon, P. Carver, and C.P. Britt. 2002. Yield improvements through modification of planting density and harvest frequency in short rotation coppice *Salix spp.* - 1. Yield response in two morphologically diverse varieties. Biomass Bioenergy 22:15-25.

Burke, M.K., and D.J. Raynal. 1994. Fine root growth phenology, production, and turnover in a northern hardwood forest ecosystem. Plant Soil 162:135-146.

Caputo, J., S. Balogh, T.A. Volk, L. Johnson, M. Puettman, B.R. Lippke, and E. Oneil. 2013. Incorporating uncertainty analysis into life-cycle analysis (LCA) of short-rotation willow biomass (*Salix spp.*) crops. Bioenergy Res. DOI 10.1007/s12155-013-9347-y

Cardinael, R., N. Thevathasan, A. Gordon, R. Clinch, I. Mohammed, and D. Sidders. 2012. Growing woody biomass for bioenergy in a tree-based intercropping system in southern Ontario, Canada. Agroforest. Syst. 86:279-286.

Christersson, L. 1986. High technology biomass production by *Salix* clones on a sandy soil in southern Sweden. Tree Physiol. 2 (1-2-3):261-272.

Christersson, L. 1987. Biomass production by irrigated and fertilized *Salix* clones. Biomass 12:83-95.

Christersson, L. 2006. Biomass production of intensively grown poplars in the southernmost part of Sweden: observations of characters, traits and growth potential. Biomass Bioenergy 30:497-508.

Christersson, L., L. Sennerby-Forsse, and L. Zsuffa. 1993. The role and significance of woody biomass plantations in Swedish agriculture. For. Chron. 69:687-693.

Clinch, R.L., N.V. Thevathasan, A.M. Gordon, T.A. Volk, and D. Sidders. 2009. Biophysical interactions in a short rotation willow intercropping system in southern Ontario, Canada. Agric Ecosyst Environ 131:61-69.

Corredor, A.H, K. Van Rees, and V. Vujanovic. 2012. Changes in root-associated fungal assemblages within newly established clonal biomass plantations of *Salix spp*. For. Ecol. Manage. 282: 105-114.

Corredor, A. H, K. Van Rees, and V. Vujanovic. 2014. Host genotype and health status influence on the composition of the arbuscular mycorrhizal fungi in *Salix* bioenergy plantations. For. Ecol. Manage. 314:112–119.

Corseuil, H.X., and F.N. Moreno. 2001. Phytoremediation potential of willow trees for aquifers contaminated with ethanol-blended gasoline. Water Res. 35:3013-3017.

Dickmann, D.I. 2006. Silviculture and biology of short-rotation woody crops in temperate regions: then and now. Biomass Bioenergy 30:696-705.

Ens, J., R.E. Farrell, and N. Bélanger. 2013a. Effects of edaphic conditions on site quality for *Salix purpurea "Hotel"* plantations across a large climatic gradient in Canada. New Forests 44:899–918.

Ens, J., R.E. Farrell, and N. Bélanger. 2013b. Early effects of afforestation with willow (*Salix purpurea, "Hotel"*) on soil carbon and nutrient availability. Forests 4:137-154.

Environment Canada - National Climate Data and Information Archive (EC-NCD). 2008. Climate data online: 1840–2008 [Online]. Available by Environment Canada http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html

Ericsson, T. 1984. Nutrient cycling in willow. IEA/ENFOR joint report. Canadian Forestry Service, Ottawa.

Ericsson, T. 1994. Nutrient cycling in energy forest plantations. Biomass Bioenergy 6:115-121.

Ferm, A., J. Hytönen, and J. Vuori. 1989. Effect of spacing and nitrogen fertilization on the establishment of biomass production of short rotation poplar in Finland. Biomass 18:95-108.

Girouard, P., C. Zan, B. Mehdi, and R. Samson. 1999. Economics and carbon offset potential of biomass fuels – final report. Resource Efficient Agricultural Production, Quebec, Canada.

Greer, E., S.R. Pezeshku, and F.D. Shields. 2006. Influences of cutting diameter and soil moisture on growth and survival of black willow, *Salix nigra*. J. Soil Water Conserv. 61:311-324.

Grigal, D.F., and W.E. Berguson. 1997. Soil carbon changes associated with short-rotation systems. Biomass Bioenergy 14:371-377.

Grogan, P., and R. Matthews. 2002. A modelling analysis of the potential for soil carbon sequestration under short rotation coppice willow bioenergy plantations. Soil Use Manage. 18:175-183.

Gruenewald, H., B.K.V. Brandt, B.U. Schneider, O. Bens, G. Kendzia, and R.F. Hüttl. 2007. Agroforestry systems for the production of woody biomass for energy transformation purposes. Ecol. Eng. 29:319-328.

Guidi, W., and M. Labrecque. 2010. Effects of high water supply on growth, water use, and nutrient allocation in willow and poplar grown in a 1-year pot trial. Water Air Soil Pollut. 207:85-101.

Gunderson, J.J., J.D. Knight, and K.C.J. Van Rees. 2008. Relating hybrid poplar fine root production, soil nutrients, and hydrocarbon contamination. Bioremediation 12:156-167.

Hangs, R.D. 2013. Biomass production and nutrient cycling in short-rotation coppice willow (*Salix spp.*) bioenergy plantations in Saskatchewan, Canada. Ph.D. dissertation. University of Saskatchewan, Saskatoon, Canada.

Hangs, R.D., J.J. Schoenau, and K.C.J. Van Rees. 2012a. A novel pre-treatment for rapidly separating willow roots from high clay content soil. Biomass Bioenergy 46:793-800.

Hangs, R.D., J.J. Schoenau, K.C.J. Van Rees, and J.D. Knight. 2012b. The effect of irrigation on nitrogen uptake and use efficiency of two willow (*Salix spp.*) biomass energy varieties. Can. J. Plant Sci. 92 (3):563-575.

Hangs, R.D., J.J. Schoenau, K.C.J. Van Rees, N. Bélanger, and T. Volk. 2013. Leaf litter decomposition and nutrient release characteristics of several willow varieties within short-rotation coppice plantations in Saskatchewan, Canada. Bioenergy Res. (In Press).

Soil Sci. Soc. Am. J.Accepted paper, posted 03/17/2014. doi:10.2136/sssaj2013.08.0368

Hangs, R.D., J.J. Schoenau, K.C.J. Van Rees, and H. Steppuhn. 2011. Examining the salt tolerance of willow (*Salix spp.*) bioenergy species for use on salt-affected agricultural lands. Can. J. Plant. Sci. 91:509-517.

Hansen, E.A. 1993. Soil carbon sequestration beneath hybrid poplar plantations in the north central United States. Biomass Bioenergy 5:431-436.

Hasselgren, K. 1998. Use of municipal waste products in energy forestry: highlights from 15 years of experience. Biomass Bioenergy 15:71-74.

Heller, M.C., G.A. Keoleian, M.K. Mann, and T.A. Volk. 2004. Life cycle energy and environmental benefits of generating electricity from willow biomass. Renew. Energy 29:1023-1042.

Heller, M.C., G.A. Keoleian, and T.A. Volk. 2003. Life cycle assessment of a willow bioenergy cropping system. Biomass Bioenergy 25:147-165.

Hendrick, R., and K. Pregitzer. 1996. Temporal and depth-related patterns of fine root dynamics in northern hardwood forests. J. Ecol. 84:167-176.

Hofmann-Schielle, C., A. Jug, F. Makeschin, and K.E. Rehfuess. 1999. Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany. I. Site-growth relationships. For. Ecol. Manage. 121:41-55.

Hoogwijk, M., A. Faaij, B. Eickhout, B. de Vries, and W. Turkenburg. 2005. Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. Biomass Bioenergy 29 (4):225-257.

Hytönen, J. 1995. Ten-year biomass production and stand structure of *Salix aquatica* energy forest plantation in southern Finland. Biomass Bioenergy 8:63-71.

Hytönen, J. 1996. Biomass production and nutrition of short-rotation plantations. University of Helsinki, Helsinki, Finland.

Hytönen, J., and S. Kaunisto. 1999. Effect of fertilization on the biomass production of coppiced mixed birch and willow stands on a cut-away peatland. Biomass Bioenergy 17:455-469.

Ingestad, T., and G.I. Ågren. 1984. Fertilization for maximum long-term production. In: Perttu, K.L. (ed) Ecology and management of forest biomass production systems. Swedish University of Agricultural Sciences, Department of Ecology and Environmental Research, Report 15: 155-165.

Jackson, R.B., H.A. Mooney, and E.D. Schulze. 1997. A global budget for fine root biomass, surface area, and nutrient contents. Proc. Natl. Acad. Sci. USA 94:7362-7366.

Johnson, D., L. Kershaw, A. MacKinnon, and J. Pojar. 1995. Plants of the western Boreal Forest and Aspen Parkland. Lone Pine Publishing, Edmonton, Alberta.

Karrenberg, S., S. Blasser, J. Kollmann, T. Speck, and P.J. Edwards. 2003. Root anchorage of saplings and cutting of woody pioneer species in a riparian environment. Funct. Ecol. 17:170-177.

Keller, C., D. Hammer, A. Kayser, W. Richner, M. Brodbeck, and M. Sennhauser. 2003. Root development and heavy metal phytoextraction efficiency: comparison of different plant species in the field. Plant Soil 249:67-81.

Keoleian, G.A., and T.A. Volk. 2005. Renewable energy from willow biomass crops: life cycle energy, environmental and economic performance. Crit. Rev. Plant Sci. 24:385-406.

Kering, M.K., T.J. Butler, J.T. Biermacher, and J.A. Guretzky. 2012. Biomass yield and nutrient removal rates of perennial grasses under nitrogen fertilization. Bioenergy Res. 5 (1):61-70.

Kiernan, B.D., T.A. Volk, P.J. Tharakan, C.A. Nowak, S.P. Phillipon, L.P. Abrahamson, and E.H. White. 2003. Clone-site testing and selections for scale-up plantings. Final program report. Prepared for the U.S. Department of Energy under cooperative agreement DE-FC36-96GO10132. .

Konecsni, S.M. 2010. Fertilization of willow bioenergy cropping systems in Saskatchewan, Canada. M.Sc. thesis. University of Saskatchewan, Saskatoon, Canada.

Kopp, R.F., L.P. Abrahamson, E.H. White, T.A. Volk, C.A. Nowak, and R.C. Fillhart. 2001. Willow biomass production during ten successive annual harvests. Biomass Bioenergy 20:1-7.

Kowalik, P.J., and P.F. Randerson. 1994. Nitrogen and phosphorus removal by willow stands irrigated with municipal waste water: a review of the Polish experience. Biomass Bioenergy 6:133-139.

Kummerow, J., M. Kummerow, and L.Trabaud. 1990. Root biomass, root distribution and the fine-root growth dynamics of *Quercus coccifera L.* in the garrigue of southern France. Plant Ecol. 87:37-44.

Labrecque, M., and T.I. Teodorescu. 2005. Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern Quebec (Canada). Biomass Bioenergy 29:1-9.

Lal, R. 2009. Soil quality impacts of residue removal for bioethanol production. Soil Tillage Res. 102 (2):233-241.

Lemus, R., and R. Lal. 2005. Bioenergy crops and carbon sequestration. Crit. Rev. Plant Sci. 24:1-21.

Leuschner, C., D. Hertel, I. Schmid, O. Koch, A. Muhs, and D. Holscher. 2004. Stand fine root biomass and fine root morphology in old-growth beech forests as a function of precipitation and soil fertility. Plant Soil 258:43-56.

Liedgens, M., and W. Richner. 2001. Minirhizotron observation of the spatial distribution of the maize root system. Agron. J. 93:1097-1104.

Maynard, D.G., Y.P. Kalra, and J.A. Crumbaugh. 2007. Nitrate and exchangeable ammonium nitrogen. In: Carter, M.R. and E.G. Gregorich (eds.) Soil sampling and methods of analysis, 2nd ed. CRC Press, Boca Raton, Florida, USA, pp. 71-80.

Mele, P.M., I.A.M. Yunusa, K.B. Kingston, and M.A. Rab. 2003. Response of soil fertility indices to a short phase of Australian woody species, continuous annual crop rotations or a permanent pasture. Soil Tillage Res. 72:21-30.

Mitchell, C.P. 1995. New cultural treatments and yield optimisation. Biomass Bioenergy 9 (1-5):11-34.

Mola-Yudego, B., and J.R. Gonzales-Olabaria. 2010. Mapping the expansion and distribution of willow plantations for bioenergy in Sweden: lessons to be learned about the spread of energy crops. Biomass Bioenergy 34:442-448.

Mosseler, A. 1990. Hybrid performance and crossability relationships in willows (*Salix L.*). Can. J. Bot. 68:2329-2338.

Moukoumi, J., R. Farrell, K.C.J. Van Rees, R.K. Hynes, and N. Belanger. 2012. Intercropping *Caragana arborescens* with *Salix miyabeana* to satisfy nitrogen demand and maximize growth. Bioenergy Res. 5:719-732.

Nadelhoffer, K.J., J.D. Aber, and J.M. Melillo. 1985. Fine roots, net primary production, and soil nitrogen availability: a new hypothesis. Ecology 66:1377-1390.

Nicoullaud, B., D. King, and F. Tardieu. 1994. Vertical distribution of maize roots in relation to permanent soil characteristics. Plant Soil 159:245-254.

Norby, R.J., P.J. Hanson, E.G. O'Neill, T.J. Tschaplinski, J.F. Weltzin, R.A. Hansen, W. Cheng, S.D. Wullschleger, C.A. Gunderson, N.T. Edwards, and D.W. Johnson. 2002. Net primary productivity of a CO2-enriched deciduous forest and the implications for carbon storage. Ecol. Applic. 12:1261-1266.

Norby, R.J., J. Ledford, C.D. Reilly, N.E. Miller, and E.G. O'Neill. 2004. Fine root production dominates response of a deciduous forest to atmospheric CO2 enrichment. Proc. Natl. Acad. Sci. USA 101:9689-9693.

Ostonen, I., K. Lohmus, and K. Pajuste. 2005. Fine root biomass production and its proportion of NPP in a fertile middle-aged Norway spruce forest: comparison of soil core and ingrowth core methods. For. Ecol. Manage. 212:264-277.

Pacaldo, R., T.A. Volk, and R. Briggs. 2011. Carbon balance in short rotation willow (*Salix dasyclados*) biomass crop across a 20-year chronosequence as affected by continuous production and tear-out treatments. Asp. Appl. Biol. 112:131-138.

Pacaldo, R.S., T.A. Volk, and R. Briggs. 2013. Greenhouse gas potential of shrub willow biomass crops based on below- and aboveground biomass inventory along a 19-year chronosequence. Bioenergy Res. 6:252-262.

Puttsepp, I. 2004. Effects of sustainable management practices on fine-root systems in willow (*Salix viminalis, S. dasyclados*), grey alder (*Alnus incana*) and Norway spruce (*Picea abies*) stands. Ph.D. dissertation. Swedish University of Agricultural Sciences, Uppsala, Sweden.

Puttsepp, U., K. Lohmus, and A. Koppel. 2007. Decomposition of fine roots and alpha-cellulose in a short rotation willow (*Salix spp.*) plantation on abandoned agricultural land. Silva Fenn. 41:247-258.

Quaye, A., and T.A. Volk. 2013. Biomass production and soil nutrients in organic and inorganic fertilized willow biomass production systems. Biomass Bioenergy (In Press).

Quaye, A.K., T.A. Volk, S. Hafner, D.J. Leopold, and C. Schirmer. 2011. Impacts of paper sludge and manure on soil and biomass production of willow. Biomass Bioenergy 35 (7):2796-2806.

Rockwood, D.L., C.V. Naidu, D.R. Carter, M. Rahmani, T.A. Spriggs, C.Lin, G.R. Alker, J.G. Isebrands, and S.A. Segrest. 2004. Short-rotation woody crops and phytoremediation: opportunities for agroforestry? Agroforest. Syst. 61:51-63.

Rytter, R.-M. 1999. Fine-root production and turnover in a willow plantation estimated by different calculation methods. Scand. J. Forest Res. 14:526-537.

Rytter, R.-M. 2001. Biomass production and allocation, including fine-root turnover, and annual N uptake in lysimeter-frown basket willows. For. Ecol. Manage. 140:177-192.

Rytter, R.-M. 2012. The potential of willow and poplar plantations as carbon sinks in Sweden. Biomass Bioenergy 36 (0):86-95.

Rytter, R.-M., and A.-C. Hansson. 1996. Seasonal amount, growth and depth distribution of fine roots in an irrigated and fertilized *Salix viminalis L.* plantation. Biomass Bioenergy 11:129-137.

Rytter, R., and L. Rytter. 1998. Growth, decay, and turnover rates of fine roots of basket willows. Can. J. For. Res. 28:893-902.

Sanchez, F.G., M. Coleman, C.T. Garten Jr., R.J. Luxmoore, J.A. Stanturf, C. Trettin, and S.D. Wullschleger. 2007. Soil carbon, after 3 years, under short-rotation woody crops grown under varying nutrient and water availability. Biomass Bioenergy 31:793-801.

Scholz, V., and R. Ellerbrock. 2002. The growth productivity, and environmental impact of the cultivation of energy crops on sandy soil in Germany. Biomass Bioenergy 23 (2):81-92.

Sennerby-Forsse, L. 1995. Growth processes. Biomass Bioenergy 9:35-43.

Singh, J.S., W.K. Lauenroth, H.W. Hunt, and D.M. Swift. 1984. Bias and random errors in estimators of net root production: a simulation approach. Ecology 65:1760-1764.

Smith, C.T. 1995. Environmental consequences of intensive harvesting. Biomass Bioenergy 9:161-179.

Soil Landscapes of Canada Working Group (SLC). 2006. Soil Landscapes of Canada v3.1 (digital map and database at 1:1 million scale). Agriculture and Agri-Food Canada. (http://sis.agr.gc.ca/cansis/nsdb/slc/v3.1/intro.html).

Stadnyk, C.N. 2010. Root dynamics and carbon accumulation of six willow clones in Saskatchewan. M.Sc. thesis. University of Saskatchewan, Saskatoon, Canada.

Steele, S.J., S.T. Gower, J.G. Vogel, and J.M. Norman. 1997. Root mass, net primary production and turnover in aspen, jack pine and black spruce forests in Saskatchewan and Manitoba, Canada. Tree Physiol. 17:577-587.

Stolarski, M.J., S. Szczukowski, J. Tworkowski, and A. Klasa. 2011. Willow biomass production under conditions of low-input agriculture on marginal soils. For. Ecol. Manage. 262 (8):1558-1566.

Swamy, S.L., A. Mishra, and S. Puri. 2006. Comparison of growth, biomass and nutrient distribution in five promising clones of *Populus deltoides* under an agrisilviculture system. Bioresour. Technol. 97:57-68.

Tharakan, P.J., T.A. Volk, C.A. Nowak, and L.P. Abrahamson. 2005. Morphological traits of 30 willow clones and their relationship to biomass production. Can. J. For. Res. 35:421-431.

Vargas, R., and M.F. Allen. 2008. Dynamics of fine root, fungal rhizomorphs, and soil respiration in a mixed temperate forest: integrating sensors and observations. Vadose Zone J. 7:1055-1064.

Verwijst, T. 2001. Willows: an underestimated resource for environment and society. For. Chron. 77 (2):281-285.

Volk, T.A., L.P. Abrahamson, K.D. Cameron, P. Castellano, T. Corbin, E. Fabio, G. Johnson, Y. Kuzovkina-Eischen, M. Labrecque, R. Miller, D. Sidders, L.B. Smart, K. Staver, G.R. Stanosz, and K. Van Rees. 2011. Yields of biomass crops across a range of sites in North Amercia. Asp. Appl. Biol. 112:67-74.

Volk, T.A., L.P. Abrahamson, C.A. Nowak, L.B. Smart, P.J. Tharakan, and E.H. White. 2006. The development of short-rotation willow in the northeastern United States for bioenergy and bioproducts, agroforestry and phytoremediation. Biomass Bioenergy 30:715-727.

Volk, T.A., L.P. Abrahamson, and E.H. White. 2001. Root dynamics in willow biomass crops. Interim Report. United States Department of Energy, Syracuse, New York.

Volk, T.A., and V.A. Luzadis. 2009. Willow biomass production for bioenergy, biofuels, and bioproducts in New York. In: Solomon, B.D. and V.A. Luzadis (eds) Renewable energy from forest resources in the United States. Routledge Explorations in Environmental Economics. Routledge, New York, pp 238-260.

Vujanovic, V., and M. Labrecque. 2002. Biodiversity of pathogenic mycobiota in *Salix* bioenergy plantations, Québec. Can. Plant Dis. Surv. 82:138-139.

Weih, M., L. Asplund, and G. Bergkvist. 2011. Assessment of nutrient use in annual and perennial crops: a functional concept for analyzing nitrogen use efficiency. Plant Soil 339 (1):513-520.

Weih, M., and N.-E. Nordh. 2002. Characterising willows for biomass and phytoremediation: growth, nitrogen and water use of 14 willow clones under different irrigation and fertilisation regimes. Biomass Bioenergy 23:397-413.

Weih, M., and N.-E. Nordh. 2005. Determinants of biomass production in hybrid willows and prediction of field performance from pot studies. Tree Physiol. 25 (9):1197-1206.

Zalesny, R.S.Jr., M.W. Cunningham, R.B. Hall, J. Mirck, D.L. Rockwood, S. J.A., and T.A. Volk. 2011. Woody biomass from short rotation energy crops, In J. Zhu, et al., ed. Sustainable production of fuels, chemicals, and fibers from forest biomass (Ch. 2), ACS Symposium Series; American Chemical Society: Washington, DC, 2011.

Zan, C.S., J.W. Fyles, P. Girouard, and R.A. Samson. 2001. Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec. Agric. Ecosyst. Environ. 86:135-144.

Figure captions

Fig. 1 Mean (N=96) nitrogen (N) and phosphorus (P) whole soil-willow system budget (kg ha^{-1}) for the initial 4-yr establishment period, including the coppice year and first 3-yr rotation, of willow SRC plantations of several willow cultivars established at different locations across Saskatchewan, Canada.

Fig. 2 Mean (N=96) potassium (K) and sulphur (S) whole soil-willow system budget (kg ha^{-1}) for the initial 4-yr establishment period, including the coppice year and first 3-yr rotation, of willow SRC plantations of several willow cultivars established at different locations across Saskatchewan, Canada.

Fig. 3 Mean (N=96) calcium (Ca) and magnesium (Mg) whole soil-willow system budget (kg ha^{-1}) for the initial 4-yr establishment period, including the coppice year and first 3-yr rotation, of willow SRC plantations of several willow cultivars established at different locations across Saskatchewan, Canada.

Tables

Table 1 A list of references, ordered by province in Canada and state in the U.S.A., with findings and data from research work in willow SRC systems that are summarized in the current manuscript.

State or Province, Country	Reference	State or Province, Country	Reference
Alberta, Canada	Ens et al. (2013a; 2013b)	Delaware; Maryland; Minnesota U.S.A.	Caputo et al. (2013)
	Corredor et al. (2012)		Kiernan et al. (2003)
			Volk et al. (2006; 2011)
Saskatchewan, Canada	Amichev et al. (2011; 2012)		
	Ens et al. (2013a; 2013b)	New York, U.S.A.	Abrahamson et al. (1998; 2002)
	Corredor et al. (2012; 2014)		Adegbidi and Briggs (2003)
	Hangs (2013)		Adegbidi et al. (2001; 2003)
	Hangs et al. (2011; 2012a; 2012b; 2013)		Arevalo et al. (2005)
	Konecsni (2010)		Ballard et al. (2000a; 2000b)
	Moukoumi et al. (2012)		Caputo et al. (2013)
	Stadnyk (2010)		Heller et al. (2003; 2004)
			Keoleian and Volk (2005)
Manitoba, Canada	Ens et al. (2013a; 2013b)		Kiernan et al. 2003
			Kopp et al. (2001)
Ontario, Canada	Cardinael et al. (2012)		Pacaldo et al. (2011; 2013)
	Clinch et al. (2009)		Quaye and Volk (2013)
	Ens et al. (2013a; 2013b)		Quaye et al. (2011)
			Volk et al. (2001; 2006; 2009; 2011)
Quebec, Canada	Girouard et al. (1999)		
	Guidi and Labrecque (2010)	Pennsylvania, U.S.A.	Kiernan et al. (2003)
	Labrecque and Teodorescu (2005)		Volk et al. (2006)

	Vujanovic and Labrecque (2002) Zan et al. (2001)	Vermont, U.S.A.	Caputo et al. (2013) Kiernan et al. (2003) Quaye and Volk (2013) Volk et al. (2006; 2011)
Connecticut; Wisconsin U.S.A.	Caputo et al. (2013) Volk et al. (2006; 2011)		
Michigan, U.S.A.	Volk et al. (2006)		

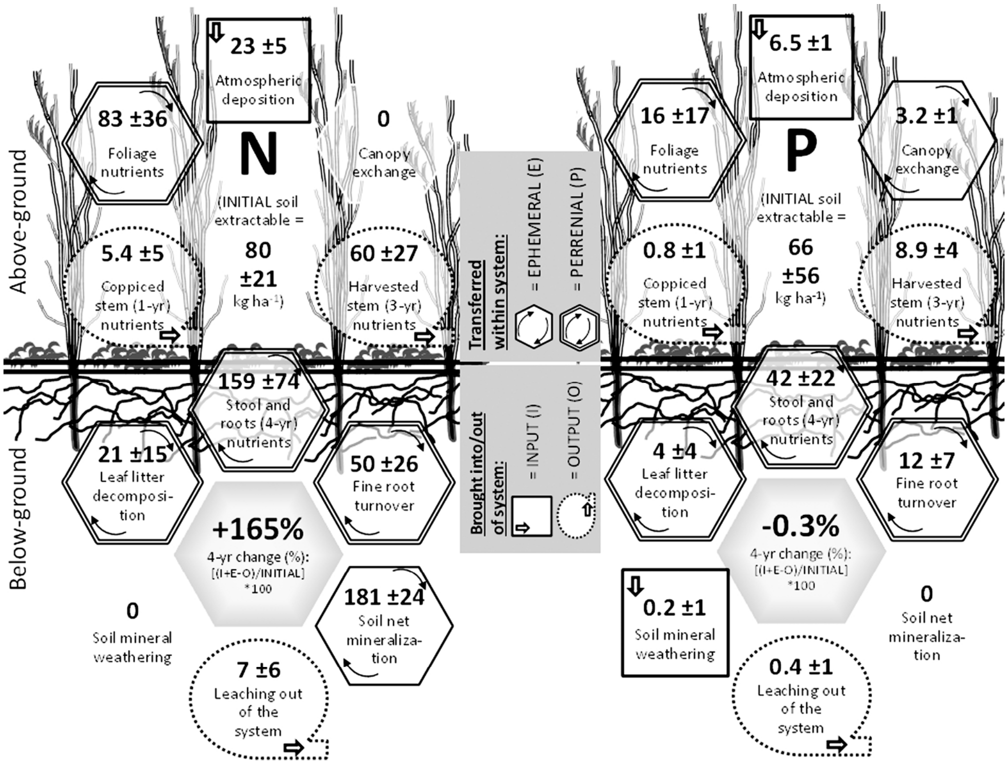
Table 2 Soil total N and available mineral N between the end of the first and second growing seasons in Saskatchewan, Canada.

Site	Type of analysis	† NO_3-N (mg kg^{-1})		$[NO_3^- + NH_4^+]$-N (mg kg^{-1})	
		End of 1st season	End of 2nd season	End of 1st season	End of 2nd season
Harris	‡ All treatments combined	27.9a (2.72)	8.08b (2.71)	30.8a (2.71)	13.6b (0.92)
	‡ Willow monocultures only	23.5 (6.08)	7.09 (1.04)	27.7 (6.77)	11.6 (2.12)
Saskatoon 1	All treatments combined	34.0a (2.42)	4.27b (0.28)	40.2a (2.54)	4.55b (0.32)
	Willow monocultures only	38.5a (2.20)	4.48b (0.12)	43.7a (2.16)	4.51b (0.13)
Saskatoon 2	All treatments combined	7.53a (0.79)	3.27b (0.52)	10.1a (0.82)	3.49b (0.53)
	Willow monocultures only	5.81 (1.85)	7.37 (3.47)	9.23 (1.89)	8.16 (3.08)

† Values in parentheses indicate standard error.

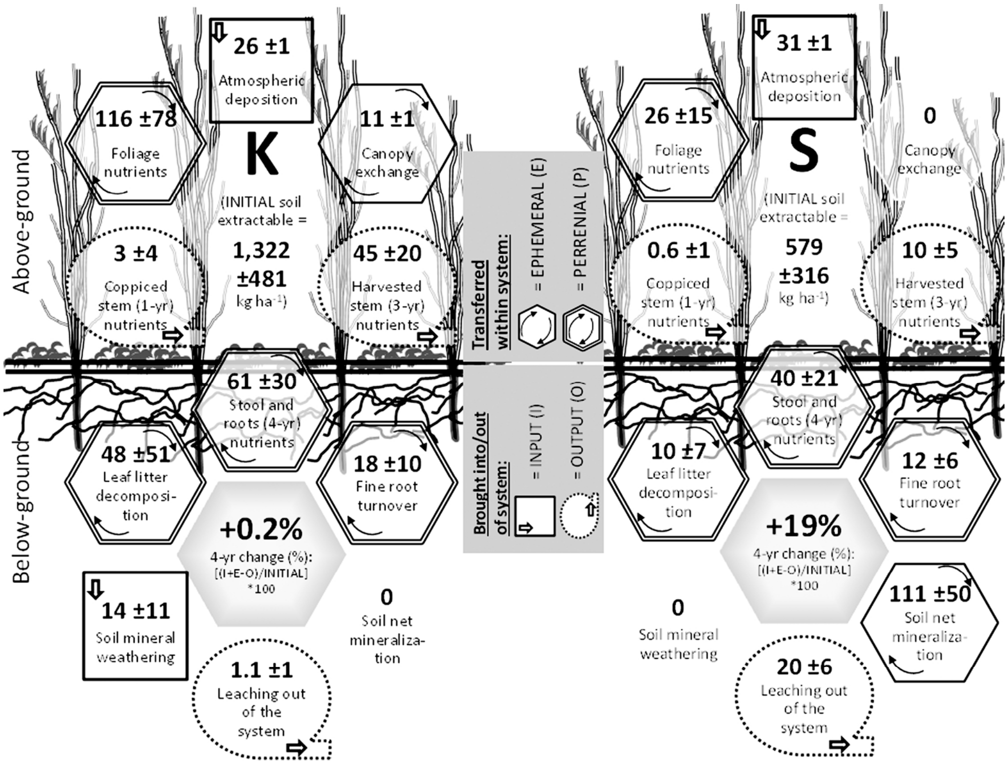
‡ A significant difference between the end of the first and second growing seasons (within a site) is indicated by different letters. "All treatments combined" means that all treatment plots were included in the analysis, whereas "Willow monocultures" means that only the willow monoculture plots were tested.

Soil Sci. Soc. Am. J.Accepted paper, posted 03/17/2014. doi:10.2136/sssaj2013.08.0368

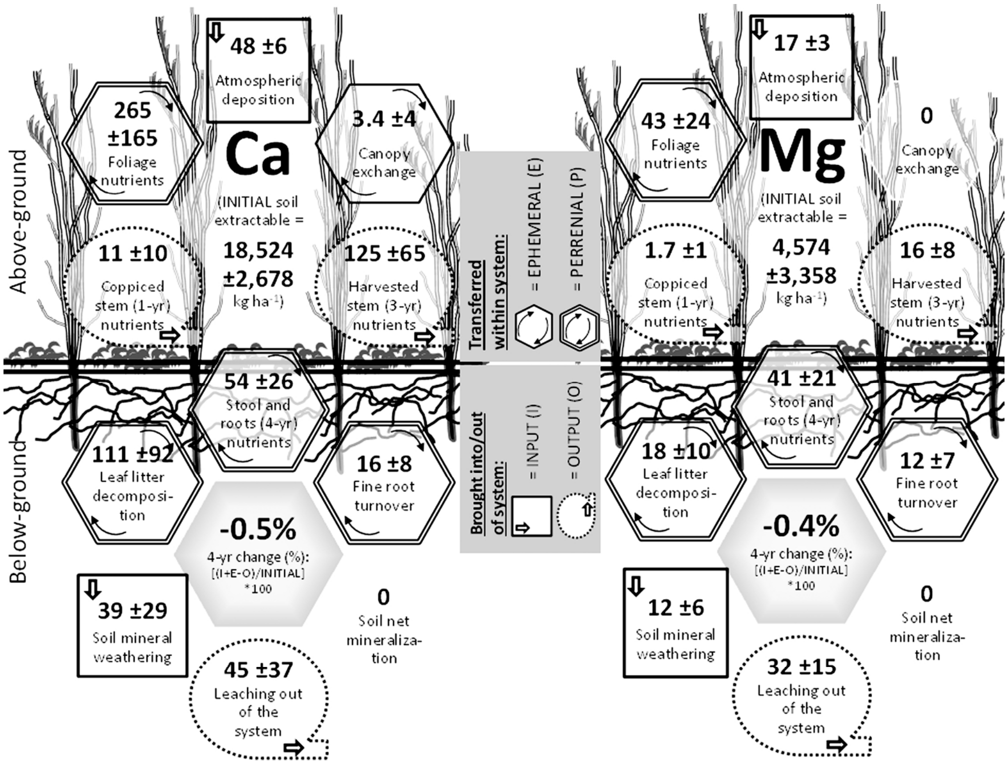


Mean (N=96) nitrogen (N) and phosphorus (P) whole soil-willow system budget (kg ha-1) for the initial 4-yr establishment period, including the coppice year and first 3-yr rotation, of willow SRC plantations of several willow cultivars established at different locations across Saskatchewan, Canada.
192x145mm (300 x 300 DPI)

Soil Sci. Soc. Am. J.Accepted paper, posted 03/17/2014. doi:10.2136/sssaj2013.08.0368



Mean (N=96) potassium (K) and sulphur (S) whole soil-willow system budget (kg ha-1) for the initial 4-yr establishment period, including the coppice year and first 3-yr rotation, of willow SRC plantations of several willow cultivars established at different locations across Saskatchewan, Canada.
192x145mm (300 x 300 DPI)



Mean (N=96) calcium (Ca) and magnesium (Mg) whole soil-willow system budget (kg ha-1) for the initial 4-yr establishment period, including the coppice year and first 3-yr rotation, of willow SRC plantations of several willow cultivars established at different locations across Saskatchewan, Canada.
192x145mm (300 x 300 DPI)