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Long-term biomass productivity of willow bioenergy plantations maintained in southern Quebec, Canada

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ABSTRACT

Maintaining the long-term productivity of short-rotation coppice plantations is very important to ensure the large-scale deployment of biomass as a renewable energy source. In Quebec (Canada), willow short rotation coppice has been studied since the early '90s, thereby allowing long-term analysis of the dynamic performance of several species and hybrids as well as management practices. In this study, we report on the long-term productivity of two trials maintained in southern Quebec and carried out to compare a) growth and biomass yield of willow *Salix viminalis* (cultivar 5027) grown for 15 years under fertilized and unfertilized conditions and b) growth of different willow cultivars over three successive rotations (10 years). The first trial showed that after four rotations, sludge-fertilized *S. viminalis* 5027 produced significantly more biomass, 19.2 odt ha^{-1} yr^{-1}, whereas unfertilized plots yielded 13.8 odt ha^{-1} yr^{-1}. The second trial showed that among the wide variety of commercial willow cultivars available, SX64 and SX61 along with some indigenous species (i.e. S25, S365, S546) were the most suitable for short-rotation forestry in southern Quebec.

1. Introduction

The intensive culture of trees for biomass is a response to the global imperative of reducing greenhouse gases and increasing energy production from renewable sources. The use of dedicated non-food crops is therefore becoming increasingly popular worldwide [1]. Willow short-rotation coppice (SRC) is one of the most promising bioenergy-cropping systems for temperate regions. In the Canadian province of Quebec, research on this practice dates back to the early '90s, when initial trials aimed at testing the suitability of willow production for Quebec agriculture were carried out. Most of these initiatives were intended to test such crops under Quebec's climatic conditions, thereby providing practical information to farmers looking to bioenergy crops as a means to increase their income [2,3].

Fast-growing woody species such as willow shrubs (*Salix* spp.) have been shown to have a positive energy balance [4] and also benefit native farm-scale biodiversity [5,6]. In addition, growing willows in short-rotation coppice on marginal agricultural lands can be economically viable [7]. The main advantages of SRC relates to the biological characteristics of willows (*e.g.* perennial growth habit, ability to develop a large number of sprouts on stumps after each coppicing cycle and

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exceptional biomass yields). In addition, the cultivation of regionally-adapted willow cultivars can protect soil and water resources and create a socially acceptable ecological habitat [8].

While most agronomic aspects of this technique have been thoroughly investigated over the last 20 years [9], little information is available on the lifespan of a willow plantation over the course of several harvest cycles. Although some studies have been published recently on long-term willow productivity, they refer to very different growing conditions such as cut-away peatlands in Finland [10], which are quite distinct from the highly-productive farmlands of southern Quebec. Other studies have reported on the productivity of SRC willow cultivars on agricultural lands, but in these cases the information either does not extend beyond the first and second rotations [11–13] or focuses on stand dynamic rather than biomass productivity [14].

The aim of this work is to provide information about the evolution of biomass productivity of willow short-rotation coppice using trials established several years ago. In particular, we have investigated: *i*) the effect of four rotations (14 years) on a single willow species under fertilized and unfertilized conditions and *ii*) the responses of nine different willow cultivars over three successive rotations (10 years).

Table 1 – Soil properties of sites S1 and S2 at establishment.

Component	Units	Site S1	Site S2
Sand	%	9	2
Silt	%	42	48
Clay	%	49	50
Texture		Clay	Clay silt
Organic matter	wt%	5.5	9.1
pH		6.4	5.7
Available P	kg ha^{-1}	34	30.2
Available K	kg ha^{-1}	438	256
Available Ca	kg ha^{-1}	8460	7650
Available Mg	kg ha^{-1}	2419	2118
CEC	meq 100 g^{-1}	33.78	32.4
B	mg kg^{-1}	0.7	1
Cd	mg kg^{-1}	–	9.2
Cu	mg kg^{-1}	4.9	2.63
Fe	mg kg^{-1}	228.4	177
Mn	mg kg^{-1}	21.2	50.1
Zn	mg kg^{-1}	2.7	3.42

Soil texture was determined by granulometric analysis; total nitrogen was measured using the Kjeldhal method; and P, K, Ca, and Mg were extracted by Mehlich-3 digestion and determined using Inductively Coupled Plasma Mass Spectrophotometry (ICP-MS).

2. Materials and methods

2.1. Study area and site characteristics

The study was carried out in the Upper St-Lawrence region (45°08′ N, 74°08′ W) 90 km southwest of Montreal, on former farmlands. The climate of the area is continental and characterized by an annual average temperature of 6.4 °C, and annual average precipitation of 954 mm (*i.e.* 767 mm of rain and 187 mm of snow). Temperatures and rainfall were constantly monitored throughout the duration of the trials. Two experimental sites were laid.

2.2. Long-term response of willow to fertilization with sewage-sludge derived fertilizer

A first trial (S1), was set up during the spring of 1995 with *Salix viminalis* (cultivar 5027) at a density of 20,000 cuttings per hectare (0.33 m between the plants of a row and 1.5 m between rows). The soil was prepared by ploughing and disc harrowing in the spring before planting. Weed control was only performed during the establishment year by two applications of glyphosate (Roundup). Initial soil properties are shown in Table 1. The experiment consisted of a randomized split-plot design with six blocks, each block divided in two sub-plots (490 m^2) corresponding to a control treatment (not fertilized, NF) and application of wastewater sludge treatment (fertilized, F). The plots were fertilized in the spring after each harvest with a level of nitrogen based on the theoretically available N for the first season following application (available N = inorganic N + 0.30 organic N) per kg of sludge dry matter. The dose of fertilizer varied among rotations and was respectively 100 kg of available N ha^{-1} at the end of the first rotation, 50 kg of available N ha^{-1} at the end of the second, 212 kg of available N ha^{-1} at the end of the third, for an overall supply of 362 kg N ha^{-1} for the duration of the experiment. More details on sludge characteristics are available in Labrecque and Teodorescu [15]. During the last 15 years, the plantation was harvested (coppiced) four times: 1997, 2001, 2004 and 2008, resulting in two rotations of four years (2–4) and two rotation cycles of three years (1–3).

2.3. Response of different willow cultivars to three rotation cycles

The second trial (S2) was established in 1999 with 10 willow cultivars (Table 2) on former agricultural land (about 500 m from S1) and soil characteristics are reported in Table 1. Before planting, perennial weeds were removed by applying 2.5 L ha^{-1} of glyphosate.

The soil was then prepared by ploughing and disc harrowing in the spring before planting. Immediately after manual planting, a mixture of preemergent herbicides (7.5 kg ha^{-1} of Devrinol and 1.5 kg ha^{-1} of Simazine) was also applied on the rows. Plant spacing was 0.33 m on the row and 1.67 m between rows, for a planting density of 18,000 cuttings per hectare. The experiment consisted of four blocks, each divided into 10 plots corresponding to the 10 studied willow cultivars. Plants were harvested three times at the end of the 2002, 2005 and 2009 growing seasons. Thus, coppicing cycles varied between three and four years. Sewage-sludge-derived fertilizer (equivalent to 100 kg available-N ha^{-1}) was supplied to all plots at the beginning of the second rotation, in 2003. In spring 2006, an additional single dose of mineral fertilizers was applied (100 kg N ha^{-1}). Throughout the study, no irrigation or pest or disease control was performed on the site. After the second coppicing cycle, a severe rust infection (*Melampsora allii-fragilis*) followed by high mortality of the