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Estimating the yield potential of short-rotation willow in Canada using the 3PG model

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2 Estimating the yield potential of short-rotation willow in Canada using the 3PG model

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Abstract: The ability to predict short-rotation coppice (SRC) willow productivity for a given region would be very helpful for large-scale deployment of this crop. The objectives of this study were to calibrate and validate the 3PG model for two commonly used clones (SX64 and SX67) and to provide yield potential estimates for 16 sites across Canada. One dataset for each clone, including leaf area index (LAI) and stem biomass was used for calibrating parameters controlling leaf and stem growth. All other datasets, coming from 8 different willow plantations, were used for model validation. Model performance was good in predicting stem biomass for the SX64 (normalized mean error [NME] = -8%, normalized root mean square error [NRMSE] = 22%) and SX67 (NME = -3%, NRMSE = 16%) clones. Predictions were more scattered for LAI, with NRMSE close to 35% and 33% and NME of 1% and 8% for SX64 and SX67, respectively. The simulation results show that the highest yields were obtained with the three-year rotation for the SX67 clone, whereas a two-year rotation seemed to be more appropriate for the SX64 clone. The simulation results also show that growing degree-days had a significant impact on yield potential which varied from 10.5 to 16.5 t DM ha⁻¹ for SX64 and from 7.5 to 11.5 t DM ha⁻¹ for SX67.

Key words: modelling, energy crop, willow, SX64, SX67, LAI, biomass

Résumé: La possibilité de prédire la productivité de taillis à courte rotation (TCR) de saule pour une région donnée serait d'une grande utilité pour le développement à grande échelle de ce type de culture. Les objectifs de ce travail étaient de calibrer et de valider le modèle 3PG pour deux clones couramment utilisés (SX64 et SX67) et fournir des estimations de rendements potentiels pour 16 sites à travers le Canada. Un jeu de données expérimentales par clone, incluant des mesures de surface foliaire et de biomasse des tiges, a été utilisé pour calibrer les paramètres contrôlant la croissance des feuilles et des tiges. Les autres jeux de données, venant de 8 plantations différentes, ont été utilisés pour la validation du modèle. La performance du modèle était bonne pour prédire la biomasse de tiges pour les clones SX64 (NME = -8 %, NRMSE = 22 %) et SX67 (NME = -3 %, NRMSE = 16 %). Les prédictions étaient plus dispersées pour l'indice de surface foliaire (LAI) avec des NRMSE proches de 35 % et 33 % ainsi que des NME de 1 % et 8 % pour les clones SX64 et SX67, respectivement. Les résultats des simulations ont démontré des rendements plus élevés pour la rotation sur trois ans avec le clone SX67, alors que la rotation sur deux ans semblerait être plus adéquate pour le clone SX64. Les résultats des simulations ont aussi montré que les degrés-jour de croissance ont un impact significatif sur le potentiel de rendement qui varie de 10.5 à 16.5 t DM ha⁻¹ pour le SX64 et de 7.5 à 11.5 t DM ha⁻¹ pour le SX67.

Mots-clés: modélisation, culture énergétique, saule, SX64, SX67, LAI, biomasse

Introduction

Willow (*Salix* spp.) is a perennial crop with a strong root system and rapid growth, thereby minimizing nutrient outflow and increasing soil carbon over time (Abrahamson et al. 1998). Willow can be used for soil phytoremediation or as a riparian buffer while also providing feedstock for biofuel or bioproducts (Cunniff and Cerasuolo 2011; Volk et al. 2006). Numerous models have been developed to predict the productivity of forest stands based on various inputs. Some of those models have been designed and/or modified to simulate the productivity of short-rotation coppice (SRC) willow, but only a few of them have been calibrated and validated to predict willow growth in Canada (Amichev et al. 2011).

Most of the willow growth models were initially developed and validated in northern Europe. Sannervik et al. (2006) determined the productivity of willow on Swedish sites based on two main processes: solar radiation intercepted by the canopy and shoot mortality. Their model was good at predicting biomass yield for the first year ($R^2 = 0.81$), but they suggested that other factors not in their model were likely to influence yield, given that they obtained a very low correlation coefficient for the second year of growth ($R^2 = 0.13$). Larsen et al. (2014) demonstrated that willow yield is strongly dependent on climate, soil, management, and clone. Those authors observed significant interactions between these variables that are needed to predict willow growth accurately. Several models, such as SOILN-FORESTSR (Eckersten 1994), ForestGrowth (Tallis et al. 2013), and WIMOVAC (Wang et al. 2015), are able to take into account this soil–climate–clone interaction. These models predicted stem biomass fairly well under northern European growing conditions.

By adding new components for perennial crops to LINTUL, a model that simulates the growth of some annual energy crops, Jing et al. (2012) designed a generic process-based model named LINPAC that was validated using worldwide data. It is a generic model that can use either site-specific or globally gridded soil and climate data. The model simulates the growth of four species: willow, reed canarygrass, miscanthus, and eucalyptus, with satisfying results for the first three species. The 3PG (Physiological Processes Predicting Growth) model predicts tree growth with site-specific climate and soil data and species-specific physiology data. This model was initially developed for eucalyptus in Australia by Landsberg and Waring (1997) and has since been used for multiple species and environments (Sands 2004). Because it was initially developed for persistent foliage, the original 3PG model did not simulate an annual cycle of leaf growth and senescence. However, the model has been used to predict yield for other species around the globe, including willow (clone SV1) in Saskatchewan, Canada (Amichev et al. 2011, 2015).

The simulation of willow growth involves several challenges. First, the great variability of yield potential between clones measured on experimental sites (Labrecque and Teodorescu 2005; Amichev et al. 2015) needs to be considered by calibrating clone-specific parameters. Second, the strong interaction between site and clone needs to be taken into account by using a model able to represent local soil and climate conditions. Lastly, the model needs to be able to simulate a complete harvest cycle, which typically varies from two to four years. Previous studies have shown that three- or four-year harvest cycles were more productive than shorter or longer cycles (Kopp et al. 1997; Szczukowski et al. 2005; Krzyżaniak et al. 2015). In addition, another study showed that,

after an extensive root system had developed during the first rotation, subsequent rotations yielded about 35% higher biomass on average (Zalesny et al. 2011). Recent studies also showed that change in yield between first and second rotations in willow (*Salix spp.*) biomass crops was strongly related to the level of first rotation yield (Sleight et al. 2016). Considering these challenges, the objectives of the present study were (1) to modify the 3PG model for simulating annual leaf growth and senescence, (2) to calibrate and validate the 3PG model growth parameters of two more clones (SX64 and SX67 of the species *Salix miyabeana*) commonly used in Canada, and (3) to estimate, with the 3PG model, the yield potential of these two clones for various locations across Canada with different harvest-cycle lengths.

Materials and methods

Field data were collected in the province of Quebec, Canada, on two sites with contrasting weather conditions and soil properties. All experimental data came from willow plantations that were already coppiced one time, except two plantations that were coppiced in 2012 (Table 1). Measurements were taken over three consecutive growing seasons: 2012, 2013, and 2014.

Site description

The first site was located in St-Roch-de-l’Achigan (Quebec, Canada; 45°50’06.6”N; 73°38’05.0”W) in the Mixedwood Plains ecozone. This site was specialized in willow production, with over 300 ha under willow cultivation since 2006. The soils on this site are mainly Dark Gray Gleysolic with a clay loam texture (Ste-Rosalie soil series; Table 2). Some plantations were on Gleyed Podsol soils with a sandy texture (Aston soil series), and others were on Brown Forest soils with a clay loam texture (Dorval soil

series). Average plant density at the time of measurement was 14 850 plants ha⁻¹ (1.82 m between single rows, and 0.37 m between the centres of individual plants). The plantations included SX64 and SX67 clones from multiple planting dates. Precipitation for the three years was above the 1971–2000 normal by 12 to 16% (Table 3). Growing degree-days (GDD; 5°C basis) during the growing season were also above the normal, especially in 2012 (+ 297 GDD).

The second site was located in La Pocatière (Quebec, Canada; 47°22'33.1"N; 70°02'17.1"W) in the Atlantic Maritime ecozone. Data were collected from two specific experimental plots (subsites). The first one was located near the shore of the St. Lawrence River (about 1 km south). The soils on this subsite were mainly Peaty Gleysol with a clay loam texture (De l'Anse soil series; Table 2). Average stand density at the time of measurement on this subsite was 16 447 plants ha⁻¹ (1.90 m between single rows, and 0.32 m between the centres of individual plants). The plantations were composed only of SX64 clones. The second subsite was 5 km south of the St. Lawrence River. The soils on this subsite were mainly Orthic Podzol with a sandy loam texture (St-André soil series). Average stand density at the time of measurement on this subsite was 14 850 plants ha⁻¹ (1.82 m between rows, and 0.37 m between plants). The plantations included both SX64 and SX67 clones. Precipitation during the growing season was close to the 1971–2000 normal in 2012 and 2013 and below normal in 2014 (-14%). Growing degree-days were above normal for the three years by 149, 58 and 242 GDD in 2012, 2013 and 2014 respectively (Table 3). In later sections of this paper, results identified as from La Pocatière include both subsites.

Field measurements

On both sites (St-Roch-de-l'Achigan and La Pocatière), data collection was performed approximately every month from the end of April to the end of October in 2012, 2013, and 2014. In total, 17 different plantations of willow were measured throughout the three-year study. The two outer rows of each plantation were generally excluded to eliminate edge effects (except for plantations on the river subsite in La Pocatière, which were composed of only four rows).

The measurements were taken in two steps. In the first step, three groups of five consecutive living plants were randomly selected from each plantation to be part of the dataset, and each individual stem was identified. Those plants were then monitored for the span of the study. On each measurement date, three values were recorded for each individual stem: stem diameter at 30 cm above the ground (D_{30}) in millimetres, stem diameter at 130 cm above the ground (D_{130}) in millimetres, and an indication about whether the stem was alive or dead. Diameters were measured using a digital caliper. A stem was considered dead if it had no green leaves and was dry.

In the second step, on each measurement date, six stems that were not among the stems in the first step were measured (D_{30} and D_{130}) and then cut to be weighed. These additional stems were selected to be representative of the minimum, average, and maximum stem diameters measured in the first step. The leaves were removed on site and stored separately from the stems. A subsample of 30 leaves per stem was weighed, and cumulated leaf area was measured with a leaf area meter (LI-3100; Licor, Lincoln, NE, USA) in order to calculate the specific leaf area (SLA). The SLA value and the total leaf biomass of each of the six stems were then used to calculate the total leaf area (TLA) of

each respective stem. Stem diameters (D_{30} and D_{130}) were measured in order to establish a relationship with the measured TLA of a stem using the following equation:

$$(1) \quad TLA = aD^b$$

where a and b are constants determined experimentally, and D is either D_{30} or D_{130} .

This relationship was then used to estimate the leaf area of each of the five consecutive living plants monitored in the first step.

Field measurements showed no plant mortality on any of the plantations, but mortality of the individual stems was observed in every plantations. The average annual stem survival rate was calculated as the percentage of individual stems still living at the end of a growing season compared to the number of living stems at the end of the previous season. At the end of the three-year cycle, the cumulative stem survival rate was calculated as the percentage of individual stems still living. This cumulative stem survival rate was calculated only for plantations which had been monitored for their three first successive years of growth.

Statistical criteria

Several statistical criteria were used to evaluate model performance. They were calculated as follows:

The Nash–Sutcliffe model efficiency coefficient (EF) was calculated to estimate the agreement between predicted and measured values, with an optimal value of 1.0:

$$(2) \quad EF = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (P_i - \bar{O})^2}$$

where n is the number of measurements, O_i is the measured value, $\bar{O}$ is the mean of the measured values, and P_i is the value predicted by the model. A negative efficiency indicates that the mean of measurements is a better predictor than the model itself is. A value greater than 0 is the minimum value for good performance in plant-growth prediction (Yang et al. 2014).

The mean error (ME), with an optimal value of 0, and its relative value in percent (normalized mean error, NME):

(3)
$$ME = \frac{1}{n} \sum_{i=1}^n (O_i - P_i)$$

(4)
$$NME = 100 \left(\frac{ME}{\bar{O}} \right)$$

The root mean square error (RMSE), with an optimal value of 0, and its relative value in percent (normalized root mean square error, NRMSE):

(5)
$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (O_i - P_i)^2}$$

(6)
$$NRMSE = 100 \left(\frac{RMSE}{\bar{O}} \right)$$

The RMSE represents the error of prediction of the model by giving more importance to high errors. A lower RMSE indicates better model simulations. The RMSE has the same unit as the variable of interest, whereas the NRMSE is the RMSE normalized by the average of measurements.

Mass model for biomass calculation

A relationship between the diameter of a stem and its dry mass was established in order to estimate the biomass of the studied plantations. A local and independent database was

used to determine the mass model (Fig. 1a). This database is a collection of previous willow stem measurements from 2009 to 2012 (Savoie et al. 2013) for willow clones SX64 and SX67 in different locations in the province of Quebec, Canada. The data include the diameter at 10 cm above the ground (D_{10}), the diameter at 130 cm above the ground (D_{130}), an estimation of the diameter at 30 cm above the ground (D_{30} , a linear interpolation between D_{10} and D_{130}), the fresh mass, the dry mass (DM), and an indication of whether the mass measurements did or did not include leaves. A group of stems without leaves was used for the mass model calibration: 69 measurements for SX64 and 93 measurements for SX67. The relationship between stem diameter and DM was estimated as an equation of exponential nature, as follows:

$$(7) \quad (DM) = aD^b$$

The determination of the DM of SX64 and SX67 clones was performed with all D_{30} data from both clones. Lupi et al. (2015) showed that a clone-specific model provided better biomass estimation accuracy for poplar clones, but the gain in model accuracy was very small for SX64 and SX67 willow clones (the decrease in NRMSE was less than 0.4% for a specific model vs. a generic model). Consequently, it was decided to calibrate a common equation for both clones, as follows:

$$(8) \quad DM = 0.106D_{30}^{2.54}$$

Where DM is in grams and D_{30} is in millimetres. The measurements from 2012 to 2014 were used to validate the model (Fig. 1b). The validation dataset was composed of 425 stems of SX64 and 258 stems of SX67. The measurements included D_{30} , D_{130} , and the DM of the stem without leaves.

Overall, the validation of the mass model performance was good, with a small bias (NME = 5.4%), a fairly good NRMSE (29%), and very good EF (0.96) and R^2 (0.95).

3PG model

The 3PG model is a dynamic, process-based model of forest growth that runs on monthly time steps using monthly climate data, information about the site, initial conditions of the plantation, and a set of parameters adapted to the species of the plantation. Over the years, further developments and experiments have been carried out with 3PG. The result has been the development of 3PGpjs: an Excel spreadsheet-based interface for 3PG (Sands and Landsberg 2002). Changes to the original 3PG model have been made in the 3PGpjs version, mainly in the way the model is parameterized. Only the set of parameters used in the 3PGpjs model are presented here.

Some modifications were made to the code of the 3PGpjs Excel spreadsheet (3PGpjs Version 2 beta, 2001) in order to simulate the growth and fall of leaves every year and also to take into account the long winter period in eastern Canada.

The first modification is the time at which leaves become mature. To implement this modification, the time variable *StandAge* (in years) was changed for the *month* variable (month of the year) in Eq. 9. This modification implies that leaves will reach maturity on a yearly basis, rather than on a lifetime basis. The output variable modified in the code, *SLA*, represents the SLA and is equal to the parameter *SLA1* when leaves are mature.

$$(9) \quad SLA = SLA1 + (SLA0 - SLA1) e^{(-\ln 2 \left(\frac{month}{tSLA}\right)^2)}$$

where SLA is the SLA ($\text{m}^2 \text{kg}^{-1}$); $SLA1$ is the SLA of mature leaves; $SLA0$ is the SLA at the beginning of the simulation (time = 0); and $tSLA$ is the age in months at which SLA is the average between $SLA0$ and $SLA1$, expressed in months of the year.

The second modification resets the weight of foliage (variable WF in t DM ha^{-1}) every spring. This ensures that the model will generate a leaf area index (LAI) value that is great enough to start a new growing season when no measured values are available for model initialization. The WF is reset to 0.5 t DM ha^{-1} in April of each growing season following the initial growing season, which represents the average measured leaf biomass on that date on both study sites.

The third modification was to add a line of code in the calculation of the frost modifier function ($fFrost$) to avoid negative values. The growth modifier $fFrost$ directly influences the gross primary production of the plantation in a given month. If the value of $fFrost$ is negative, the result would be a negative gross primary production. A negative value can happen when each day in a 31-d month is a frost day while parameter kF is set to its maximum value of 1. This scenario happens frequently in a region such as eastern Canada, where winter is relatively cold. This was corrected by setting $fFrost$ equal to 0 if it has a negative value.

The fourth modification was done by adding a monthly age modifier function to the multi-annual age modifier function. Variable $StandAge$ was replaced by variable $month$ (Eq. 10), and new parameters ($MaxAge2$, $rAge2$, and $nAge2$) were added, thereby influencing $fAge$ over the course of a single year. The growth modifier $fAge$ is thus now

dependent on the age of the plantation (*StandAge*, in years) and the month of the year (*month*).

$$(10) \quad fAge = \left(\left(1 + \left(\frac{StandAge}{MaxAge \cdot rAge} \right)^{nAge} \right) \left(1 + \left(\frac{month}{MaxAge2 \cdot rAge2} \right)^{nAge2} \right) \right)^{-1}$$

where *MaxAge* is a parameter (in years) affecting plant production as a function of the plantation's lifetime, *rAge* is the relative stand age (relative to *MaxAge*) when there will be a 50% growth reduction, *nAge* is the intensity of the growth reduction associated with the *MaxAge* variable, *MaxAge2* is a parameter (in months) affecting plant production as a function of the time of the year, *rAge2* is the relative stand age (relative to *MaxAge2*) when there will be a 50% growth reduction, and *nAge2* is the intensity of the growth reduction associated with the *MaxAge2* variable.

Lastly, the calculation of the litterfall rate was also modified so that it is a function of the month in the current year, rather than a function of the age of the plantation over its lifespan. In the definition of *litterfall*, the variable *StandAge* was therefore replaced by the variable *month*.

Model initialization and calibration/validation

Information about the plantations and their initial state was collected for each site. The beginning of simulations (initial year and month) was set as the first date of actual field measurements. The end of the simulations was generally set after three years of growth, as that is a common lifespan for SRC plantations, except for plantations that were measured in their fourth year of growth (i.e. for which the end was set to four years). The measured leaf and stem biomass (in t ha⁻¹) during the first field data collection (usually at the end of April) was used to initialize *WF* and the weight of stem (*WS* in t DM ha⁻¹)

variables. Because the root weight of the plant was never measured, this value had to be estimated. Data from Bouman and Sylliboy (2012) suggest that, 90 days after planting, the weight of roots (WR) of an SX64 plant is about 15% of the mass of its stem. The Initial WR value was therefore estimated as 15% of the initial WS value for both SX64 and SX67. The measured stem density was used to initialize the stocking parameter (stems per hectare). The initial available soil water (ASW) was set at field capacity. The weather data collected with an on-site weather station were used to generate the monthly climate data required to run 3PGpjs. Missing weather data were retrieved from the nearest Environment Canada weather stations (distance < 15 km) (Environment Canada 2016).

Calibration of the 3PGpjs model was performed by adjusting the values of the growth parameters using data from two plantations (table 1). Two different parameter sets were calibrated: one for the SX64 clone and one for the SX67 clone. Several methods were used to calibrate the crop growth parameters. Some parameters were adjusted using measured data, other parameters were calibrated by minimizing the differences between observed and predicted LAI and stem biomass, and some parameter values were defined using the calibration performed previously by Amichev et al. (2011) for the SV1 clone. Default 3PGpjs values were used for parameters that were not calibrated.

During the calibration and validation steps, the model's accuracy was evaluated by comparing measured LAI and stem biomass with predicted values. Several statistical criteria (EF, ME, NME, RMSE, and NRMSE) were used to evaluate the model's performance.

Yield potential estimation

In total, 16 sites, covering as much as possible the arable land of Canada, were chosen for the run of simulations of the calibrated 3PGpjs model (Fig. 2). Ten of those sites were located in eastern Canada, and six were located in western Canada. A total of 192 growth scenarios were tested: 16 sites $\times$ 2 clones (SX64 and SX67) $\times$ 2 soil types (sandy loam and clay loam) $\times$ 3 harvest strategies (harvested every two, three, and four years). For each scenario, 24 years of growth were predicted using historical climate data from 1976 to 1999 retrieved from Environment Canada weather stations (Environment Canada 2016). The two soil types were characterized by minimum and maximum *ASW* over 1 meter depth of, respectively, 51 and 120 mm for the sandy loam soil and 245 and 378 mm for the clay loam soil. Initial soil water content in April was set at the maximum *ASW*. All simulations were initialized in April with an initial foliage biomass of 0.5 t DM ha⁻¹, an initial stem biomass of 0.9 t DM ha⁻¹, and an average stem density of 140 000 stems ha⁻¹, which were the average values measured on the two experimental sites. Cumulative predicted yield was calculated for two-, three-, and four-year rotation cycles over 24 years, thereby providing distributions for a fair comparison of the different harvest strategies.

Results and Discussion

Yield measurements at the two experimental sites

The average dry mass yield measurements of the SX64 and SX67 willow clones for year of growth 1, 2, 3 and 4 are presented in Table 4. These measurements show that, on average, the SX64 clone produced more annual biomass than the SX67 clone did (*t*-test, $P < 0.01$). Labrecque and Teodorescu (2005) also reported greater annual yield for SX64 (16.9 t ha⁻¹) than for SX67 (9.4 t ha⁻¹) in southern Quebec. For the SX64 clone, the yield

of the first year was significantly lower than the yield of the second and third years (t -test, $P < 0.05$) at St-Roch-de-l'Achigan, but no significant trend was observed at La Pocatière. For the SX67 clone, the trend was less clear, with a tendency of yield decrease year after year at St-Roch-de-l'Achigan and higher yields for years of growth two and three than for the first year of growth at La Pocatière. The average annual stem survival rate was 94% for SX64 and 87% for SX67. At the end of the three-year cycle, the cumulative stem survival rate was 77% for SX64 and 48% for SX67. The lower stem survival rate of SX67 may partly explain why SX67 had smaller biomass growth than SX64 after its first year of growth.

On their first date of measurement, the St-Roch-de-l'Achigan plantations had a willow average density of 141 000 stems ha^{-1} for SX64 and 139 300 stems ha^{-1} for SX67 while the La Pocatière plantations had an average density of 115 000 stems ha^{-1} for SX64 and 144 700 stems ha^{-1} for SX67. There was no relationship between stem density at the beginning of a growing season and the survival rate of the plantation in that year.

However, observations show that all stems survived a growing season when the density was below 90 000 stems ha^{-1} and that the mortality was high (up to 46% depending on the plantation) when density was above 200 000 stems ha^{-1} . Stem mortality seems to follow the same relation with density as previous observation made on plant mortality. Indeed, Kopp et al. (1997) observed with the SV1 clone that a greater plant density resulted in a lower survival rate.

Model calibration

Values of the calibrated growth parameters for the two clones are presented in Table 5.

Allometric relationships were estimated using experimental data, whereas the partitioning

parameters were optimized. Optimized values of leaf biomass proportions ($pFS2$, $pFS20$) were greater for SX67 than for SX64 and were close to the experimentally measured proportions when LAI was at maximum (typically in July and August, varying between 0.3 and 0.4). Although a relationship between the foliage-to-stem mass ratio and the stem diameter can be defined at each measurement date, no clear relationship between these two variables was found when data from the complete growing season were used. Consequently, a constant ratio was assumed ($pFS2 = pFS20$). Root biomass was not measured in this experiment, so the parameter controlling the minimum proportion of the net primary production sent to root biomass was estimated from a previous study (Amichev et al. 2011), whereas the maximum proportion was calibrated by minimizing the differences between predicted and measured LAI and stem biomass of the calibration dataset. These values of minimum (7.5%) and maximum (15%) proportion of the net primary production sent to root were close to the range of values measured in previous studies (e.g. Proe et al., 2002). However, more recent studies showed that the root to shoot ratio can be greater because biomass of fine roots was often largely underestimated (Pacaldo et al., 2013; Cunnif et al., 2015). Values of the temperature modifier parameters were kept similar to those proposed by Amichev et al. (2011) for the SV1 clone. Default 3PG values were used for the frost modifier, soil water modifier, and fertility rating parameters. As explained in the Materials and Methods section, the age modifier section was substantially modified. Most parameters controlling the annual and multi-annual age modifier functions were calibrated by minimizing the differences between predicted and measured LAI and stem biomass of the calibration dataset. Similar parameter values for both clones were calibrated for the annual age modifier function ($MaxAge2$, $nAge2$, and

374 *rAge2*), whereas clone-specific parameters were calibrated for the multi-annual function
375 (*MaxAge*, *nAge*, and *rAge*). Calibration datasets showed that the annual growth of the
376 SX64 clone tended to increase every year for the three studied years (Fig. 3a), whereas
377 the annual growth of the SX67 clone tended to decrease after two years of growth
378 (Fig. 3b). This result explains why values of the *MaxAge* and *nAge* parameters were
379 lower for SX67 than for SX64 (Table 5). The litterfall parameters (*gammaFx*, *gammaF0*,
380 and *tgammaF*) were calibrated by minimizing the differences between predicted and
381 measured stem biomass and LAI. Similar values for both clones were found. The root
382 turnover (*Rttover*) parameter was not very sensitive, and the default value proposed by
383 Amichev et al. (2011) for the SV1 clone was used. The stomatal conductance, the stem
384 mortality, and the self-thinning parameters were not modified, and default 3PGjps values
385 were used. Concerning the canopy structure and process parameters, the SLA at the
386 beginning of the simulation (*SLA0*) and at leaf maturity (*SLA1*) were calibrated by
387 minimizing the differences between predicted and measured LAI. Both SLA parameter
388 values were slightly lower for SX67 than for SX64. Specific leaf area values were in the
389 same range as those measured throughout the experiment, as well as those reported by
390 Amichev et al. (2011) for the SV1 clone. The *tSLA* [age at which $SLA = (SLA0 +$
391 $SLA1)/2$] and *k* (coefficient of extinction) parameters were calibrated by minimizing the
392 differences between predicted and measured stem biomass and LAI. Because the net
393 radiation use efficiency needed to be increased, the value of the canopy quantum
394 efficiency (*alpha*) was increased from 0.053 to 0.065 mol_c mol_{PAR}⁻¹ which was the
395 maximum value recommended by Warring (2000). Other canopy and process parameters
396 (*fullCanAge*, *MaxIntcptn* and *LAImaxIntcptn*) as well as the parameters of the *Branch*

397 *and bark fraction* section were not modified, and default 3PG values were used.

398 Concerning the parameters of the *Conversion factors* section, the radiation-use efficiency

399 parameters (*molPAR_MJ*) were increased from 2.3 to 4.6 mol_{PAR} MJ⁻¹ which was the

400 value found by McCartney (1978) and also reported by Russel et al., (1989) for plant

401 canopies. Other parameters of the *Conversion factors* section (Table 5) were not modified

402 (3PG default values were used). The ratio of NPP/GPP (*Y*) were optimized for both

403 clones with optimized values close to the recommended range proposed by Waring et al.,

404 (1998) and Landsberg and Waring (1997) (0.47 +/- 0.04 and 0.5 respectively). After

405 modification of the *alpha*, *Y* and *molPAR_MJ* parameters, the net potential radiation use

406 efficiencies (*molPAR* x *gDM_mol* x *alpha* x *Y*) were 3.84 g DM MJ⁻¹ for the SX67 clone

407 and 3.41 g DM MJ⁻¹ for the SX64 clone. These values were slightly lower than the values

408 used by Jing et al. (2012) for simulating willow growth (4 g DM MJ⁻¹). Finally, default

409 value of the SV1 clone was used for the basic density parameters.

410 After calibration of the SX64 and SX67 growth parameters, stem dry biomass and LAI of

411 the calibration dataset were well predicted (Fig. 3), but model accuracy was better for

412 stem biomass than for LAI. For both clones, the bias of LAI predictions was small

413 (NME = -6.7% for SX64 and NME = 12.2 for SX67), NRMSE were below 30%, and EF

414 were greater than 0.6. For both clones, the maximum predicted and measured LAI varied

415 from 6 to 7 m²_{leaf} m⁻²_{soil}. These values were in the same range as those reported in other

416 studies (Kajfez-Bogataj 1990; Jing et al. 2012). Other studies reported slightly lower LAI

417 values for these clones (Tharakan et al. 2005), but this difference does not have a large

418 impact on model prediction since almost 90% of solar radiation is intercepted for LAI

419 values greater than 4 m²_{leaf} m⁻²_{soil}. Stem biomass was very well predicted for both clones,

with very low bias ($\text{NME} < 2.5\%$) and NRMSE (6.6% for SX64 and 11.3% for SX67) and high EF (>0.9). For the SX64 clone, the annual predicted yields were 12.4, 15.2, and 19 t DM ha⁻¹ yr⁻¹ for years 1, 2, and 3, respectively. The model was able to predict correctly the annual yield of the first two years (13.2 and 15.4 t DM ha⁻¹ yr⁻¹ for years 1 and 2) but slightly underestimated the yield of the third year (14.8 t DM ha⁻¹ yr⁻¹). The measured annual predicted yields of SX67 were lower and tended to decrease in the third year (11.5, 10.6, and 4.1 t DM ha⁻¹ yr⁻¹ for years 1, 2, and 3, respectively). The predicted yields of years 1 and 2 (10.1 and 11.2 t DM ha⁻¹ yr⁻¹, respectively) were very close to the measured yields, but the third-year prediction (9.4 t DM ha⁻¹ yr⁻¹) was overestimated. According to model parameterization, the higher yields of the SX64 clone could be attributed to better radiation-use efficiency and lower foliage-to-stem ratio. Linderson et al., 2007 also found that there were differences among willow cultivars in radiation use efficiency.

Model validation

The validation step showed that overall model performance was good in predicting the stem biomass of the SX64 and SX67 clones (Fig. 4a, b, Table 6). However, the model's performance was slightly better for the SX67 clone ($\text{NME} = -3.3\%$ and $\text{NRMSE} = 16\%$) than for the SX64 clone ($\text{NME} = -8.2\%$ and $\text{NRMSE} = 22.1\%$). There was slightly more scatter for LAI predictions (Fig. 4c, d), with NRMSE of close to 33% to 35% for the two clones and NME of 1.2% for SX64 and 7.7% for SX67. Model performance for stem biomass prediction was in the same range as the performance reported in other studies. Amichev et al. (2015) reported a bias of -3.3% and an NRMSE of 13.6% for various clones in Saskatchewan, Canada, with the 3PG model, Jing et al. (2012) reported an NRMSE of 17% for willow biomass prediction in Europe and the northern US with the

LINPAC model, and Tallis et al. (2013) reported an NRMSE of approximately 20% for willow biomass predictions in the UK with the ForestGrowth-SRC model. Jing et al. (2012) also reported higher values of NRMSE for LAI (35%) than for biomass (19%) for miscanthus, willow, and reed canarygrass with the LINPAC model. The average predicted annual biomass values (13.7 and 9.7 t DM ha⁻¹ for SX64 and SX67, respectively) were slightly greater than the measured values (11.4 and 8.2 t DM ha⁻¹, respectively).

Yield potential in Canada

The cumulated stem DM (t ha⁻¹) from the 24-year predictions on the 16 different sites are presented in Table 7. There is great variation in predicted biomass among sites, which confirms the large impact of climate interaction on willow yield. The predicted biomass was greater for the clay loam soil than for the sandy loam soil, but the difference was small ($\leq 2.9\%$). The harvest strategy had an influence on the predicted total harvested dry biomass. Figure 5 shows the distribution of the highest-yielding harvest strategies for 12-year rotation cycles, which was the minimum common period for comparing two-, three-, and four-year rotation cycles. The 12-year cycles were either from 1976 to 1987 or from 1988 to 1999. For SX64, the three-year and two-year rotation strategies resulted in almost the same yield with a slightly higher yield (1%) for the three-year than the two-year strategy. For SX67, the highest yielding strategy was always the two-year rotation with yield 5% greater than the three-year strategy. Considering the cost of the harvesting operations, the three-year strategy appeared to be the best economical strategy for the SX64, while further analysis would be required to determine the best economical strategy for the SX67 clone. When individual annual biomass production is considered, simulation results show that for any harvest strategy and for both clones, on average, the second

growth year had a greater yield among all growth years. For other growth years, the predicted average annual biomass of the first year was greater than the predicted average annual biomass of years 3 and 4 for SX67. This is the reason why the two-year rotation was preferable for SX67 in these simulations. For SX64, the predicted yields of years 3 and 4 were greater than the predicted yield of the first year. Thus, a longer rotation (i.e. three-year rotation) appeared to be the best harvest strategy for SX64.

The influence of climate conditions on biomass prediction was investigated. Although precipitation varied considerably (average annual amounts from 895 to 1503 mm for eastern sites and 352 to 480 mm for western sites), no relationship between cumulative precipitation and dry biomass was found, even on the sandy loam soil which has a low soil water storage capacity (difference between minimum and maximum ASW = 69 mm over 1 m depth). Such results were also reported by Njakou Djomo et al. (2015) on European sites. The cumulative GDD (from May to October) were the main climate factor influencing willow biomass. The mean cumulative GDD were 1 674°C on eastern sites and 1 466°C on western sites. Figure 6 shows the range of biomass yield over the distribution of cumulative GDD across Canada (SX64 simulations on clay loam soil with a three-year rotation scenario). A moderate correlation was found between the cumulative GDD of a site and its yield for a particular year, with R^2 ranging from 0.26 to 0.56 for eastern sites (depending on scenario and willow clone combination) and 0.12 to 0.32 for western sites (data not shown). There was also a moderate correlation between cumulative solar radiation (from May to October) and dry biomass (R^2 varying from 0.21 and 0.50 for eastern sites and 0.12 to 0.29 for western sites).

Based on these simulation results, a range of potential biomass production for a willow plantation in Canada was estimated with a three-year harvest cycle. For locations where annual GDD ranged from 1 050°C to 1 400°C, expected annual yield varies between 10.5 and 12.5 t DM ha⁻¹ for the SX64 clone and between 7.5 and 9 t DM ha⁻¹ for the SX67 clone. For locations with GDD between 1 400°C and 1 600°C, yields between 11 and 15.5 t DM ha⁻¹ and between 8.5 and 10.5 t DM ha⁻¹ can be expected for SX64 and SX67, respectively. For locations with GDD over 1 600°C, yields varying from 14 to 16.5 t DM ha⁻¹ and from 10 to 11.5 t DM ha⁻¹ can be expected for the SX64 and SX67 clones, respectively. These potential yields were in the same range as measured yields in previous studies for specific locations. Labrecque and Teodorescu (2005) reported average annual yields of 16.9 and 9.4 t DM ha⁻¹ for SX64 and SX67, respectively, on a site located 90 km southwest of Montréal, Canada (GDD > 1 800°C). In agricultural regions of Saskatchewan, Canada, where GDD range from 1 200°C to 1 600°C, Amichev et al. (2012) estimated an average annual yield between 11.4 and 15 t DM ha⁻¹ for the SV1 clone. In the northern US, Kopp et al. (1997) reported a range of annual yields slightly greater than the present predictions (between 11 and 22 t DM ha⁻¹ for various clones), which is consistent with the warmer growing conditions and longer growing season in the northern US in comparison with Canada. Measured yields reported in previous studies for the first rotation were generally lower, and comprised between 3 and 9 t DM ha⁻¹ (Hang set al., 2014; Amichev et al., 2015).

Conclusion

The 3PG model was successfully modified to predict the annual growth and senescence of leaves of two willow clones commonly used in Canada, SX64 and SX67. The

modified 3PG model was then calibrated and validated for predicting biomass growth dynamics over several years in eastern Canada. Model performance was good in predicting stem biomass for SX67 (NME = -3%, NRMSE = 16%) and SX64 (NME = -8%, NRMSE = 22%). The model was then used to estimate yield potential on various sites across Canada. The model showed that a the three-year rotation resulted in slightly higher yield than the other for SX64, whereas the two-year rotation was more appropriate for SX67. For 16 simulated locations, SX64 had greater yield than SX67 did. The range of annual potential yield was moderately correlated with available GDD and varied from 10.5 to 16.5 t DM ha⁻¹ for SX64 and 7.5 to 11.5 t DM ha⁻¹ for SX67.

This study shows that new willow clones can be easily calibrated in the 3PG model. The addition of new clones to the model could be useful for producers so that they can evaluate the potential yield for various soil and climate conditions and optimize the harvest cycle. However, further model improvements could be considered to enhance the 3PG model's capabilities. For instance, improving the simulation of nitrogen and carbon cycles could allow the model to be used not only for biomass prediction, but also for environmental assessment.

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Table 1. Year of plantation, first coppicing year and age of the stems at the time of measurement at the two experimental sites. Data used for calibration are in bold. Other data were used for model validation.

Site	Clone	Year of plantation	First coppicing year	Year of growth		
				2012	2013	2014
St-Roch	SX64	2008	2009	3	4	1
		2008	2010	2	3	4
		2007	2011	1	2	3
	SX67	2007	2009	3	1	2
		2008	2010	2	3	1
		2008	2011	1	2	3
La Pocatière	SX64	2010	2012	3	1	2
		2010	2012	3	1	2
		2010	2010	2	3	1
	SX67	2010	2010	2	3	1

Table 2. Soil and water-holding properties on the two experimental sites, St-Roch-de-l'Achigan (St-Roch) and La Pocatière (La Poc.).

Site	Soil	Soil texture	Wilting point (%vol.)	Field capacity (%vol.)	Min ASW (mm)	Max ASW (mm)
St-Roch	Ste-Rosalie	Clay loam	22	36	220	360
	Dorval	Clay loam	22	36	220	360
	Aston	Sand	5.0	10	50	100
La Poc.	St-Pâcome	Loamy sand	4.4	9.5	44	95
	De l'Anse	Clay loam	22	38	221	378

Note: ASW, available soil water over a 1-m depth.

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Table 3. Cumulative precipitation, growing degree days (GDD; 5°C basis), and solar radiation during the growing season on two experimental sites, St-Roch-de-l’Achigan (St-Roch) and La Pocatière (La Poc.).

Site		Precipitation (mm)	GDD (°C)	Radiation (MJ m ⁻²)
St-Roch	2012	627	2 187	3 366
	2013	607	1 983	3 124
	2014	620	2 025	3 117
	<i>Normal (1971-2000)</i>	<i>540</i>	<i>1 890</i>	<i>N/A</i>
La Poc.	2012	517	1 758	3 165
	2013	512	1 667	3 144
	2014	436	1 851	3 021
	<i>Normal (1971-2000)</i>	<i>507</i>	<i>1 609</i>	<i>N/A</i>

Note: Cumulative values from May to October.

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Table 4. Average measured yield and standard deviation (SD) of the SX64 and SX67 willow clones for different growth stages on the two experimental sites, St-Roch-de-l'Achigan (St-Roch) and La Pocatière (La Poc.).

Site	Year of Growth	SX64		SX67	
		Yield (t DM ha ⁻¹)	SD	Yield (t DM ha ⁻¹)	SD
St-Roch	1	9.0	4.1	10.4	3.7
	2	14.4	3.2	8.7	3.1
	3	12.8	4.9	6.5	2.8
	4	7.4	2.1	---	---
La Poc	1	10.4	3.7	5.2	1.3
	2	8.7	3.1	9.6	1.5
	3	6.5	2.8	9.6	2.2

Note: DM, dry mass; SD, Standard Deviation.

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Table 5. Growth parameters calibrated for the SX64 and SX67 willow clones and default parameters for the SV1 willow clone.*

3PGjps name	Definition	Units	Source	SX64	SX67	SV1*
Allometric relationships and partitioning						
pFS2	Foliage-to-stem ratio at $D_{130} = 2$ cm	-	Optimized	0.30	0.35	0.10050†
pFS20	Foliage-to-stem ratio at $D_{130} = 20$ cm	-	Optimized	0.30	0.35	0.19453†
StemConst	Constant in the stem mass vs. diameter relationship	-	Measured	67	67	0.11393†
StemPower	Power in the stem mass vs. diameter relationship	-	Measured	2.5	2.5	1.89062†
pRx	Maximum fraction of NPP to roots	-	Optimized	0.15	0.15	0.125
pRn	Minimum fraction of NPP to roots	-	SV1 parameterization	0.075	0.075	0.075
Temperature modifier (fT)						
Tmin	Minimum temperature for growth	°C	SV1 parameterization	5	5	5
Topt	Optimum temperature for growth	°C	3PGjps default value	20	20	20
Tmax	Maximum temperature for growth	°C	SV1 parameterization	40	40	40
Frost modifier (fFrost)						
kF	Number of production days lost for each frost day	d	3PGjps default value	1	1	1
Soil water modifier (fSW)						
SWconst	Constant in the relationship between available soil water and NPP	-	3PGjps default value	0.7	0.7	Soil-texture-dependent ‡
SWpower	Power in the relationship between available soil water and NPP	-	3PGjps default value	9	9	
Fertility rating (FR)						
M0	Value of “m” when FR = 0	-	3PGjps default value	0	0	0
fN0	Value of f_N when FR = 0	-	3PGjps default value	1	1	1
Age modifier (fAge)						
MaxAge	Maximum stand age used in plantation lifetime modifier	years	Optimized	7.33	6	4
nAge	Power of relative plantation lifetime in function for fAge (relative to MaxAge)	-	Optimized	2.44	2	4
rAge	Plantation lifetime at which production is reduced by half	-	3PGjps default value	0.95	0.95	0.95
MaxAge2	Maximum stand age used in annual age modifier	months	Optimized	12	12	-
nAge2	Power of relative plantation annual age in function for fAge (relative to MaxAge2)	-	Optimized	4	4	-
rAge2	Month at which annual production is reduced by half	-	Optimized	0.7	0.7	-
Litter fall and root turnover						
gammaFx	Maximum litterfall rate	month ⁻¹	Optimized	0.68	0.68	0
gammaF0	Litterfall rate at t = 0	month ⁻¹	Optimized	0.006	0.006	0
tgammaF	Age at which litterfall rate has median value	months	Optimized	8	9	0
Rttover	Average monthly root turnover rate	month ⁻¹	SV1 parameterization	0.002	0.002	0.002
Conductance						
MaxCond	Maximum canopy conductance	m s ⁻¹	3PGjps default value	0.02	0.02	0.02
LAigcx	Litterfall rate at t = 0	-	3PGjps default value	3.33	3.33	3.33
CoeflCond	Age at which litterfall rate has median value	mBar ⁻¹	3PGjps default value	0.05	0.05	0.05
BLcond	Average monthly root turnover rate	m s ⁻¹	3PGjps default value	0.2	0.2	0.2
Stem mortality and self-thinning						
wSx1000	Max. stem mass per tree at 1000 trees ha ⁻¹	kg tree ⁻¹	SV1 parameterization	150	150	150

3PGjps name	Definition	Units	Source	SX64	SX67	SV1*
thinPower	Power in self-thinning rule	-	3PGjps default value	1.5	1.5	1.5
mF	Fraction mean single-tree foliage biomass lost per dead tree	-	3PGjps default value	0	0	0
mR	Fraction mean single-tree root biomass lost per dead tree	-	3PGjps default value	0.2	0.2	0.2
mS	Fraction mean single-tree stem biomass lost per dead tree	-	Optimized	0.33	0.45	0.2
Canopy structure and processes						
SLA0	Specific leaf area at age 0	$\text{m}^2 \text{kg}^{-1}$	Optimized	10	8	10.753
SLA1	Specific leaf area for mature leaves	$\text{m}^2 \text{kg}^{-1}$	Optimized	16	15	13.507
tSLA	Age at which specific leaf area = (SLA0+SLA1)/2	months	Optimized	1	1	1.5 year§
k	Extinction coefficient for absorption of PAR by canopy	-	Optimized	0.6	0.6	0.5
fullCanAge	Age at canopy cover	years	3PGjps default value	0	0	1
MaxIntcptn	Maximum proportion of rainfall evaporated from canopy	-	3PGjps default value	0.15	0.15	0.15
LAImaxIntcptn	LAI for maximum rainfall interception	-	3PGjps default value	0	0	0
alpha	Canopy quantum efficiency	$\frac{\text{mol}_C}{\text{mol}_{\text{PAR}}}^{-1}$	literature reference	0.065	0.065	0.053
Branch and bark fraction (fracBB)						
fracBB0	Branch and bark fraction at age 0	-	3PGjps default value	0.75	0.75	0
fracBB1	Branch and bark fraction for mature stands	-	3PGjps default value	0.15	0.15	0
tBB	Age at which fracBB = (fracBB0+fracBB1)/2	years	3PGjps default value	1.5	1.5	0
Various						
Y	Ratio of NPP/GPP	-	optimized	0.545	0.475	0.47
Density	Basic density	t m^{-3}	SV1 parameterization	2	2	¶
Conversion factors						
Qa	Intercept of net vs. solar radiation relationship	W m^{-2}	3PGjps default value	-90	-90	-90
Qb	Slope of net vs solar radiation relationship	-	3PGjps default value	0.8	0.8	0.8
gDM_mol	Molecular weight of dry matter	g DM mol^{-1}	3PGjps default value	24	24	24
molPAR_MJ	Conversion of solar radiation to PAR	$\frac{\text{mol}_{\text{PAR}}}{\text{MJ}}^{-1}$	literature reference	4.6	4.6	2.3

Note: NPP, net primary production; PAR, photosynthetically active radiation; GPP, gross primary production; DM, dry mass.

*Parameterization performed by Amichev et al. (2011) in version 2.5 of the 3PGjps model.

†The value of these parameters is far from the parameterization for the SX64 and SX67 clones, as Amichev et al. (2011) approximated each plant as a single stem.

‡Replaced by the soil class parameters if given in the site factors.

§The modification makes this parameter monthly based rather than yearly based.

||Amichev et al. (2011) assumed that this parameter differed in every rotation of a stand. The values varied between 0.053 and 0.1119.

¶In version 2.5 of the 3PGjps model, the density is time dependent and is defined by the parameters rhoMin, rhoMax, and tRho, equal to $2.0294 \text{ t DM m}^{-3}$, $1.2513 \text{ t DM m}^{-3}$, and 2 years, respectively, as suggested by Amichev et al. (2011).

Table 6. Performance of the SX64 and SX67 parameterization of the 3PGpjs model.

Clone		RMSE	NRMSE	ME	NME
SX64	LAI ($\text{m}^2_{\text{leaf}} \text{m}^{-2}_{\text{soil}}$)	1.27	34.5%	0.05	1.2%
	Biomass (t DM ha^{-1})	4.26	22.0%	-1.58	-8.2%
SX67	LAI ($\text{m}^2_{\text{leaf}} \text{m}^{-2}_{\text{soil}}$)	1.09	33.0%	0.25	7.7%
	Biomass (t DM ha^{-1})	2.63	16.0%	-0.55	-3.3%

Note: RMSE, root mean square error; NRMSE, normalized root mean square error; ME, mean error; NME, normalized mean error; LAI, leaf area index; DM, dry mass.

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Table 7. Predicted cumulative biomass harvested over 24 years, from 1976 to 1999 (t DM ha⁻¹), for two willow clones (SX64 and SX67) on Canadian sites.

	Harvest	SX64		SX67	
Site	cycle (years)	Sandy loam	Clay loam	Sandy loam	Clay loam
<i>Eastern Sites</i>					
Mont-Joli, QC	2	308	308	238	238
	3	305	306	222	222
	4	296	296	205	205
Trenton, ON	2	383	393	291	296
	3	398	405	286	290
	4	393	402	272	275
Charlottetown, PE	2	335	338	258	259
	3	334	336	242	243
	4	326	328	226	227
Sydney, NS	2	302	303	235	235
	3	296	296	216	216
	4	285	285	198	198
Fredericton, NB	2	303	305	235	237
	3	305	306	222	223
	4	298	300	208	209
Val d'Or, QC	2	277	277	217	217
	3	273	273	200	200
	4	268	268	187	187
Bagotville, QC	2	286	286	223	223
	3	287	287	210	210
	4	277	277	194	194
St-Hubert, QC	2	351	355	268	270
	3	363	364	261	262
	4	357	360	247	248
London, ON	2	373	379	284	287
	3	385	391	277	280
	4	382	387	264	266
Greenwood, NS	2	335	337	257	258
	3	337	338	244	244
	4	330	332	229	230
<i>Western Sites</i>					
Brandon, MB	2	328	332	252	254
	3	336	342	244	247
	4	330	334	229	231
Lethbridge, AB	2	345	352	265	268
	3	351	359	254	258
	4	352	359	244	247
Swift Current, SK	2	321	327	248	251
	3	320	330	233	239
	4	311	320	218	221
Edmonton, AB	2	287	289	224	225
	3	287	287	210	210
	4	282	284	198	198
Grande Prairie, AB	2	295	297	230	231
	3	292	296	215	216
	4	290	293	203	204
Prince Albert, SK	2	300	305	233	236
	3	302	307	221	224
	4	294	299	206	208

Note: QC, Quebec; ON, Ontario; PE, Prince Edward Island; NS, Nova Scotia; NB, New Brunswick; MB, Manitoba; AB, Alberta; SK, Saskatchewan.

Fig. 1. (a) Relationship and equation between willow stem dry mass and diameter of both SX64 and SX67 established from an independent database of willow stem measurements (Savoie et al. 2013). (b) Comparison of the measured and calculated stem dry masses using the equation defined in Fig. 2a.

Fig. 2. Location of the 16 simulation sites used to estimate yield potential and distribution of the growing degree-days (5°C basis) across Canada. Source: Maps prepared by Agriculture and Agri-Food Canada's Science and Technology Branch in partnership with Environment Canada's National Service Office-Agriculture.

Fig. 3. Predicted (lines) and measured (dots) stem dry mass of the willow clones SX64 (a) and SX67 (b), and predicted and measured leaf area index (LAI) of SX64 (c) and SX67 (d) for the calibration dataset from 2012 to 2014.

Fig. 4. Predicted and measured stem dry mass of the willow clones SX64 (a) and SX67 (b), and predicted and measured leaf area index (LAI) of SX64 (c) and SX67 (d) for the calibration and validation datasets from 2012 to 2014 (St-Roch, St-Roch-de-l'Achigan; La Poc, La Pocatière).

Fig. 5. Frequency of the highest-yielding harvest strategy for the simulations on 16 sites, for both clones (SX64 and SX67).

Fig. 6. Predicted annual yield (SX64 and SX67, Clay Loam, three-year rotations) over the distribution of the growing degree-days for the 16 simulations sites across Canada (DM, dry mass).

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