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Maximum annual potential yields of Salix miyabeana SX67 in southern Quebec and effects of coppicing and stool age
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Abstract:	Aboveground biomass yields of short rotation cultures (SRC) of willow can vary substantially depending on site quality. Among others, aboveground biomass yields depend on climatic conditions, soil properties, age of the SRC and number of harvesting cycles. In this study, we investigated the effects of coppicing on growth variables (i.e. largest basal stem, height and aboveground biomass) at ten SRC of Salix miyabeana SX67 established on various soils in southern Quebec. More than 1100 shrubs with stool ages varying between one and fifteen years were measured. Strain analysis was carried out to calculate past annual aboveground productivities, and maximum annual yield potential was quantified at each site. Annual growth rates were highly variable and depended on site and coppicing history. To achieve optimal stool development and aboveground yields, two to three growing seasons following coppicing are necessary for sandy and clayey sites, respectively. The delays for reaching maximum yields were shortened when soil cation exchange capacity was dramatically low and were prolonged when soil was physically restricting stool development. This lag influenced the total yield of the first rotation and also modulated the magnitude of the increase of aboveground biomass that is generally observed in the second rotation. To increase yields in southern Quebec, our results suggest that it is preferable to extend the length of the first rotation instead of coppicing at the end of the first growing season after establishment.

Dear Drs Weih and Casler,

I am happy to submit a third revised version of the manuscript now entitled "Maximum annual potential yields of *Salix miyabeana* SX67 in southern Quebec and effects of coppicing and stool age". Again, we sincerely thank the reviewer for the time he has spent to read and comment the manuscript.

We have made the minor modifications requested.

Thank you,

Nicolas Bélanger, Professor, Université du Québec

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COMMENTS FOR THE AUTHOR:

Title
> The authors should consider using the phrase "Maximum annual yield potential" rather than Maximum annual yields" in the title to reflect that this analysis focuses on potential yields.
RESPONSE: The title has been changed accordingly.

Introduction
> P2L43 - reference 22 is a pot study that was irrigated so it may have addressed issues with water availability but not with 'precipitation' as noted here.

RESPONSE: Yes, thank you. This was changed to *''sufficient water availability''*.

Method
> P4L28 - is this the amount of active ingredient of the herbicide applied. That should be clear since formulations vary P4L52ff - this addition helps to clarify some of the issues with the sampling that was done. It is not clear why the number of stools sampled varied from 4 to 10 in a plot if the plot size was consistent (5 x 5m). It appears that the size of the plots varied across sites and was based on the number of consecutive stools samples rather than a set plot size. It would be useful if this was clarified.

RESPONSE: We have clarified both issues.
The application of herbicides: *''Roundup Pro^{TM} (41% glyphosate, the active ingredient (a.i.)) was applied once before soil ploughing in the fall at a rate of 2 to 4 L ha^{-1} (0.85 to 1.7 a.i. ha^{-1}), depending on weed type and abundance.''*

The size of the plots: *''Each measurement was performed on sixteen to fifty shrubs in four to nine plots. Plots were selected along one or two randomly selected rows, depending on the number of plots measured. Each plot was separated by at least 20 m. The sampling in each plot consisted of four to ten healthy/vigorous successive stools along the row. The size of the plots varied based on the number of stools sampled. A plot consisting of four stools was approximately 2 × 3 m, whereas a plot of ten stools was approximately 5 × 3 m.''*

> P5L18 - fewer not 'less'
RESPONSE: Thank you, this was corrected.

> P5L22 - some additional data here would help make the case that SX67 supports few stems. Reporting the number of stems per stool in the first and second would help here. As a contrast reporting the number of stems per stool for the S. eriocephala cultivar would be helpful rather than just saying the number of stems per stool was 'higher'.

RESPONSE: Indeed, this is now mentioned: *''Nissim et al. [3] reported that the number of stems per stool of SX67 did not increase significantly between the first and the third rotations. On average, it shifted from 4.5 stems per stool to 5.5 stems per stool, respectively. In comparison, Salix eriocephala Muhl shifted from an average 3.5 stems per stool at the end of the first rotation to 7.5 at the end of the third rotation [3].''*

Results
> P10L53 - Material and Methods should both be capitalized or not capitalized.

RESPONSE: Thank you, it was capitalized throughout the text.

Discussion
> P16L6ff - what is the cut off for a dramatically low CEC? The sites listed have CECs of 68, 23 and 12. Then the STR site is listed as a low CEC site and has a value of 7. Is the cut off somewhere between 7 and 12 for a low versus high CEC site.

RESPONSE: There is an effect for sites with a CEC of 12 or more. However, it is hard to set a threshold from four sites, with only STR not responding well to coppicing.

> It may be that this factor alone does not explain the differences in the growth patterns at this site and that other factors, such as water availability, may be influencing growth patterns.

RESPONSE: We agree. Therefore, we have added a short sentence to clarify this idea.

''The benefits of coppicing were obvious at sites where soil CEC was 12 $cmol_c$ kg^{-1} or over, i.e. the organic soil at the RXP site or the mineral soil with significant silt and clay at BOI2 and SJPJ2 (Table 2), favoring major increases in the area of the largest diameter and aboveground biomass yield. Conversely, no gain from coppicing was detected at the STR site as the sandy loam soil is characterized by a low CEC (7 $cmol_c$ kg^{-1}) that supports low yields. It could also be that other factors such as lower water availability due to the coarser soil texture at the STR site (sandy loam at STR compared to loam or organic soil elsewhere) may be influencing growth patterns.''

> P19L6 - it is not clear what information is being contrasted with this 'lower' statement at the start of a paragraph.

RESPONSE: Yes it is true. This statement was clarified: *''Lower aboveground yields for the first rotation compared to subsequent rotations were frequently [10] but not systematically observed [58, 59].''*

Maximum annual potential yields of *Salix miyabeana* SX67 in southern Quebec and effects of coppicing and stool age

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Abstract Aboveground biomass yields of short rotation cultures (SRC) of willow can vary substantially depending on site quality. Among others, aboveground biomass yields depend on climatic conditions, soil properties, age of the SRC and number of harvesting cycles. In this study, we investigated the effects of coppicing on growth variables (i.e. largest basal stem, height and aboveground biomass) at ten SRC of *Salix miyabeana SX67* established on various soils in southern Quebec. More than 1100 shrubs with stool ages varying between one and fifteen years were measured. Strain analysis was carried out to calculate past annual aboveground productivities, and maximum annual yield potential was quantified at each site. Annual growth rates were highly variable and depended on site and coppicing history. To achieve optimal stool development and aboveground yields, two to three growing seasons following coppicing are necessary for sandy and clayey sites, respectively. The delays for reaching maximum yields were shortened when soil cation exchange capacity was dramatically low and were prolonged when soil was physically restricting stool development. This lag influenced the total yield of the first rotation and also modulated the magnitude of the increase of aboveground biomass that is generally observed in the second rotation. To increase yields in southern Quebec, our results suggest that it is preferable to extend the length of the first rotation instead of coppicing at the end of the first growing season after establishment.

Keywords Willow, short rotation culture, fast growth, soil texture, coppicing, root system age

Introduction

The use of willows (S*alix* spp.) is considered for various ecological applications such as bioenergy [1-3], phytoremediation [4] and waste water and sludge filtration [5-7]. Willows can colonize and perform relatively well on various soil types, which makes them an interesting option for landowners with unused marginal land [2, 8]. Short rotation culture (SRC) of willow has recently grown in interest in Quebec as yields of *Salix viminalis* planted at a density of 18 000 stools ha^{-1} in the warm southern region were reported to be as high as 70 Mg ha^{-1} of dry weight (DW) after a second rotation of three years [9]. This cultivar is also known for its high potential productivity in other regions with similar temperate climates [e.g., Verwijst [10], Bergkvist, Ledin [11] in Sweden, and Stolarski [12] in northern Poland], although yields in southern Quebec appear to be in the upper tier of all yields reported for such climates. Cultivars of *S. miyabeana* also seem to be very well suited for SRC in the southern region because it has a greater resistance to insect and disease than *S. viminalis* and thus, shows more consistent yields [13].

The productivity of willows can nevertheless be negatively impacted by climate (e.g. short growing season degree days, and low precipitation and soil moisture) and soil (e.g. low nutrient availability or contaminants) [14-16]. Under certain conditions, the productivity of SRC of various willow cultivars has been reported to be quite low, i.e. 1 to 5 Mg DW ha year^{-1} (e.g. Heinsoo et al. [17] in Estonia, Tahvanainen, Rytkönen [15] in Finland, and Ens et al. [18] and Moukoumi et al. [19] in different locations in Canada, including the dry Prairie provinces with relatively short summers). In particular, climate was shown to severely impact willow biomass production. A meta-analysis conducted in Sweden on SRC of willow with high soil nitrogen (N) contents (75-165 Kg N ha^{-1}) showed that yields could be modeled at the landscape scale with radiation use efficiency as the main independent variable [20], whereas Price, Clancy [21] and Guidi, Labrecque [22] demonstrated the importance of having sufficient water availability for optimum willow productivity. Soil nutrient availability was also shown to impact willow biomass production. Increased soil N availability following fertilization generally leads to greater willow yields, especially for soils with initially low nutrient availability [9]. Soil pH and total calcium (CaO) were also shown to control *S. purpurea* yields of nine SRCs established from southern Ontario to central Alberta [18].

Willow aboveground biomass production is normally lower during the first growing season compared to subsequent years within the same rotation, whether the SRC has just been established (first rotation) or is in its second or third rotation [13, 10]. However, a meta-analysis from data of 2082 willow SRCs in Sweden showed that yields increased by 60% from the first to second rotation [23]. Similarly, Volk et al. [24] observed an asymptotic

increase of aboveground biomass from the first to the fourth rotation. This is likely explained by a delay of the rooting system to fully establish and acquire soil resources (i.e. water and nutrients). Moreover, coppicing is often done in the first stage of growth. Despite few studies on its effects on willow productivity, coppicing is reported to stimulate the production of fine roots [25]. In turn, it decreases competition by weeds and leads to resprouting of multiple and vigorous stems [26]. Coppicing of willow at initial stages tends to increase stem growth and maximum root diameter [27]. In this respect, producers will generally coppice after one full growing season of the first rotation to increase the number of stems per stool and to promote aboveground biomass production for following years. The benefits of coppicing on growth were reported to be small on sandy soils, probably because nutrient and water availability are intrinsically low. Positive coppicing effects were more frequently observed for clayey soils [28]. The gains on basal main stem diameter, height and weight induced by coppicing also varied among species and clones [3]. As a whole, however, studies on the effects of coppicing on willow growth remain relatively anecdotic and more robust scientific studies are required to identify the conditions (and timing) under which it should be conducted.

Measuring stem diameter and height as well as total aboveground biomass after a rotation of a few years is an integrative measure of site productivity [29, 30]. Telenius, Verwijst [31] showed that the strong relationships between stem diameter, height and aboveground biomass allow for the development of allometric equations for the non-destructive (i.e. mostly stem diameter measurements) but diligent estimation of biomass yields of specific cultivars with satisfactory precision. This method could be used to decide whether the stands have reached financial maturity and should be harvested. Such integrative growth data, however, does not provide the detailed information needed to fully elucidate seasonal (climate, water and nutrients), coppicing and stool age (rotation associated to harvest) effects on willow growth and biomass production. For example, Mola-Yudego, Aronsson [23] suggested that higher annualized yields from the first rotation were achieved with four growing seasons instead of five. Annual yield data could be of significant value to assess whether coppicing and number of rotations have a measurable impact on willow productivity. In this context, the objective of this study was to reconstruct annual aboveground biomass production (using a combination of stem diameters and dendrochronological measurements) in a series of willow SRCs in southern Quebec at various sites and covering different root system ages as a means to determine the impact that coppicing and rotation have had on yields.

Material and methods

Study sites

This study used a network of eighteen SRCs of *S. miyabeana* SX67 established at nine different sites in southern Quebec on various soil types (Tables 1 and 2). In all SRCs, SX67 cuttings of 20 to 25 cm in length were inserted in the soil to a depth of about 15-20 cm at an interval of 30 cm along a single row design with a spacing of 1.8 m between the rows (approximate density of 18,500 stools ha^{-1}) using a planting machine. The cuttings were from one-year-old stems of about 3 m long and 1-2 cm in diameter that showed no symptom of disease on bark or wood. For the ABI, ALB, BOI, LAV, MTL, RXP, SJPJ and STR sites, row lengths of SX67 were over 100 meters at a typical monoculture site, whereas SX67 was distributed in randomized split-blocks at the HTG site (10 × 12 m), which consists of a clonal trial. Coppicing was generally done in the fall of the first growing season. However, some SRCs were either not coppiced or coppiced after the second growing season only (see Tables 1 and 2 for details). Harvesting was generally done three to five years after coppicing. Before SRC establishment, weeds were controlled using mechanical soil preparation (i.e. where stoniness was low, ploughing in the fall of the previous year was followed by cross-disking just before spring planting). Roundup Pro^{TM} (41% glyphosate, the active ingredient (a.i.)) was applied once before soil ploughing in the fall at a rate of 2 to 4 L ha^{-1} (0.85 to 1.7 a.i. ha^{-1}), depending on weed type and abundance. The fact that the measurements were performed in SRCs with different numbers of coppicing and rotations allowed to specifically test their effects on aboveground yields (see further details in this section).

The SRCs established at the ABI, ALB, HTG, LAV, RXP and STR sites were on former agricultural soils of varying textures, whereas MTL was planted on a sandy (loamy sand) forest soil after a mixedwood stand was harvested and the soil surface had been cleared from all residues (Table 2). Most sites were characterized by slightly acidic soils (pH from 5.2 to 5.6), except for soils at the BOI and HTG sites which were near neutral (pH from 7.3 to 7.5). Also, the RXP site was the only one where SRCs were established on an organic soil (Table 2).

Field growth survey

The SRCs were monitored non-systematically at the end of the growing season between 2000 and 2013 (Table 1). Each measurement was performed on sixteen to fifty shrubs in four to nine plots. Plots were selected along one or two randomly selected rows, depending on the number of plots measured. Each plot was separated by at least 20 m. The sampling in each plot consisted of four to ten healthy/vigorous successive stools along the row. The size of the plots varied based on the number of stools sampled. A plot consisting of four stools was approximately 2 × 3 m,

4

whereas a plot of ten stools was approximately 5 × 3 m. On each sampled stool, height of the largest stem, the basal diameter at about 5 cm above the collar (later referred as largest diameter) and the number of stems per stool were measured. For each stool, all stems were then harvested for biomass measurement. Fresh weights (including the leaves) were obtained in the field using an electronic scale. Subsamples of 3 to 6 kg (integrating whole stems) were then collected, brought back to the laboratory and dried to constant weight at 70°C in an oven and reweighted to convert fresh weight to dry weight. It should be noted that sampling the stem with the largest diameter from healthy/vigorous stools was systematically applied as a means to provide a proxy for the maximum yield potential (MYP) of a site. This method was used because we were interested in reconstructing annual yields and that dendrochronological work could only be conducted on a limited number of stems per SRC. It can be considered for SX67 because studies of SX67 generally show that it produces fewer stems than other productive clones. Guidi Nissim et al. [3] reported that the number of stems per stool of SX67 did not increase significantly between the first and the third rotations. On average, it shifted from 4.5 stems per stool to 5.5 stems per stool, respectively. In comparison, *Salix eriocephala* Muhl shifted from an average 3.5 stems per stool at the end of the first rotation to 7.5 at the end of the third rotation [3]. To some extent, our approach is inspired from the methodology used in forestry to estimate site quality index for which only dominant trees (i.e. the larger stems) are selected for measurement [32, 33]. Using our approach could, however, be problematic for *Salix* clones that produce more stems and distribute much of the biomass in the smaller stems.

Soil sampling and analysis

During summer 2011, 2012 or 2013, about 300 g of soil were sampled at a depth of 0-25 cm in five plots from one SRC in each of the nine sites for which the field growth survey had been conducted (see Table 2 for specific SRCs). The samples were first air-dried in the laboratory and then sieved to pass through a 2 mm mesh. Soil pH of mineral samples were measured using a soil:water ratio of 1:2, whereas a ratio 1:10 was used for organic soil samples (i.e. RXP). Using a muffle furnace, organic C was measured by loss of ignition after 15 minutes at 575°C and then inorganic C ($CaCO_3$) after 10 minutes at 1000°C [34]. Soil particle size distribution was analyzed using the Horiba Partica LA-950v2 Laser Particle Analyzer (Horiba Instruments, Irvine, CA, USA). Samples from BOI, MTL and SJPJ were first pre-treated to destroy sesquioxides. In this respect, samples had to be bleached twice with NaOCl and thoroughly washed with distilled water. Samples from RXP contained more than 60% of organic matter and only

5

small amounts of mineral particles. Thus, the bulk of organic matter was first destroyed by loss on ignition and then treated with NaOCl before yielding enough particles for size analysis. Soil exchangeable cations were measured by atomic absorption (Varian AA-1475, Palo Alto, US) after they were extracted using an unbuferred 0.1 M BaCl$_2$ solution [35]. Cation exchange capacity (CEC) was defined as the sum of exchangeables cations (Ca, Mg, K, Na, Mn, Al and Fe).

Relationship between area of largest diameter and dry biomass

Stem and root system ages of these SRCs ranged from 1 to 7 years and from 1 to 9 years, respectively (Table 1). Hence, we identified the root age and the stem age in a single descriptor (i.e. SaRa where S is stem, R is root and a is age of the stem and root system). A linear relationship between the area of the largest diameter and aboveground biomass was tested for all available measurements. Between 2000 and 2013, aboveground biomass was measured twenty-four times at seventeen SRCs of the main eight sites. Two additional sites for which three more biomass samplings were available (as described above) were also included only for this dataset as a means to build the most robust regression model. Points from this dataset are not independent considering that more than one SRC was monitored within the same site at most of the study sites. Thus, to test the site effect as a random factor, a mixed model was also performed with the area of the largest diameter as a fixed variable using *lme* function in the nlme package (R 3.01, R Core Team 2012). This function allows unbalanced experimental design. Normality of residuals of these models was validated with the Shapiro-Wilk test, whereas conditions of homoscedasticity were validated visually.

Estimation of basal area increment

Annual productivity of SRCs at the eight sites for which the field growth survey had been conducted and sampled for soils (see ''Soil sampling year'' column in Table 1 for details) was investigated using estimates of basal area increment (BAI). Root system age, numbers of coppicing and rotations varied between these SRCs. Dendrochronological analyses were therefore carried out from a set of six to twenty-two stem sections per SRC that were sampled at about 5 cm above the collar and that also exhibited the largest diameters. This sampling was completely distinct from the field growth survey described previously as it was conducted one to two years following the main survey (i.e. in 2012 and 2013, depending of site). Strain analysis [36, 37] was performed on the disks using

a binocular coupled with WinDENDRO (Regent Instruments, Québec, Canada) after progressively sanding them with grits of 200, 400 and 600. For each stem section, a total of six rays were used to estimate the BAI of each growing season on the disk. We first calculated the total growth area corresponding to the year that the largest diameters were measured during the field survey (specific for each site). This area (i.e. sum of growth areas or BAIs) was then used as the denominator to calculate the contribution (in %) of BAI of each growing season captured on the disk, including the years following the growing season that the largest diameters were measured during the field survey. The contributions calculated on each disk were averaged by growing season for each site (Step 1, Fig. 1). The areas of the stems with the largest diameter measured during the field survey were then multiplied by the average contribution of BAI of each growing season captured at the SRC as an estimation of BAI for each respective growing season. These estimates of BAI calculated on each disk were finally averaged by growing season for each site (Step 2, Fig.1).

To validate our approach, stems with the largest basal diameters that were measured in the field in 2011 at six SRCs (i.e. ABI1, BOI1, HTG1, MTL1, LAV1 and RXP1) and other stems were again measured in 2013 in the same SRCs. The area of largest diameters measured in 2011 (9 plots × 4 stools per plot = 36 stools) were statistically compared to the 2011 estimates (5 plots × 10 stool per plot = 50 stools) obtained based on hindcasts from the stems with the largest basal diameters measured in 2013. To compare the estimated and measured values, a mixed model was developed with site as a random effect and estimated vs. measured as a fixed factor using the function *lme* of the nlme package (R 3.01, R Core Team 2012). Because the condition of normality of residuals was not met with the raw data (tested with the Shapiro-Wilk test), the mixed model was performed with log-transformed data.

Estimation of annual aboveground biomass production and maximum potential

The equation of the linear relationship between area of the largest diameter and aboveground biomass (Fig. 2) was used to hindcast annual aboveground biomass yields for the nine selected SRCs. Independence of data points was accepted based on the non-significant site effect (random factor) in the mixed model and the fact that the slopes of both models were roughly similar (see Results section). Thus, the model was used to convert the estimated BAI for each growing season to annual dry mass yields per shrub. It was then multiplied by 18,500 (i.e. the number of seedlings planted per hectare) to estimate the annual yields. The estimated annual yields are clearly overestimates

because mortality was not taken into account, but as indicated earlier, our numbers are proposed as an estimate of MYP.

At four of the sites, it was also possible to estimate annual aboveground biomass production of subsequent rotations using the same dendrochronological approach and linear model described above. At the RXP site, RXP2 (next to RXP1 and with root systems of the same age) was harvested late in the fall of 2012. We thus measured the basal diameter of the largest stem of twenty shrubs in the fall of 2013 (i.e., first growing season of the second rotation) and calculated the BAI. Also, ABI2 (next to ABI1 and with root systems of the same age) was harvested just after snow thaw in the early spring of 2012 and the basal diameter of the largest stem of twenty shrubs with two growing seasons was measured at the end of the 2013 growing season. Producers harvested SJPJ1 at the end of the 2011 growing season so that the largest basal diameter of fifty stems (5 plots × 10 stools per plot) with two growing seasons were measured again at the end of the 2013 growing season. Finally, at MTL1, we harvested SX67 for biomass measurement at the end of the 2011 growing season. Contiguous shrubs of sampled plots were also cut to facilitate handling. The same stools therefore regrew without light limitation due to an overall low height (not shown) and stem density of neighbor shrubs. The basal diameter of the largest stem of twenty shrubs was again measured on stems with two growing seasons. At ABI2, MTL1 and SJPJ1, stem sections were sampled to reconstruct the BAI of the first and second year of growth as explained above. The shrubs measured at this site were therefore assumed to be representative of MYP.

The fact that stem and root system ages were different between sites necessitated that we identified a temporal threshold for MYP for comparison, i.e. the year that the MYP was reached. On the one hand, for SRCs with only one rotation, the MYP threshold was identified as the first growing season for which the yield was not lower from those of subsequent growing seasons. This was done by determining whether the upper limit of the range encompassed by the coefficient of variation of the estimated BAI (step 2, Fig. 1) of the second growing season reached or exceeded the mean of one of the following growing season. If the second growing season did not fulfil this condition, then the procedure was repeated with the third growing season. At that point, the test was conclusive at all SRCs (i.e. MYP was reached in the third growing season or less). On the other hand, for SRCs in their second rotation or more, the MYP threshold was identified as the second year of growth of the current rotation because the first growing season following establishment or harvest is generally characterized by the lowest aboveground biomass yields, due to a high initial C demand of resprouting stems which is, in large part, satisfied by root reserves

8

[38]. Based on the assumption that annual productivity increases asymptotically [39] until MYP is reached, the problem of comparing annual productivities between one SRC for each of the eight sites is overcome by using yields that appeared to be no longer considerably limited by root development. Because the coppicing year varied between SRCs (after one or two growing seasons) and that some SRCs were not coppiced at all, the year that MYP was reached is later reported in the manuscript as the total number of years since willow establishment.

Data analysis

Mixed models were developed to explain the area of the largest diameter-to-height ratios with site as a random factor and stem age as a fixed factor. Stem age was considered as a quantitatively continuous variable as well as a binary variable, allowing the comparison between the area of the largest diameter-to-height ratios of stems with one growing season and stems with more than one growing season. Normality of residuals was tested by the Shapiro-Wilk test using the function *shapiro.test*. The R^2 of the models were obtained by squaring the r Pearson coefficients of the correlation between fitted values and raw data. Also, a linear regression was developed using the number of stems per stool as the response variable and the age of the root system as the explanatory variable.

Using one-way ANOVA, we compared growth variables (i.e. basal diameter of largest stem height and aboveground dry biomass) between shrubs of the same stem age but of different stool (or root system) ages. Because the condition of normality was not systematically fulfilled, comparisons were made by ANOVA using a permutational test [40] to overcome the deviations in the normality of the data. This assumes that ANOVA is quite robust against relative non homoscedasticity. Data were always grouped and tested by site. In several cases, the estimated basal diameters of the largest stems were compared to measured basal diameters of the largest stems from another SRC of the same site or from the same SRC but for a different rotation. This test systematically served to assess the age effect of the rooting system on growth within a site (later referred to as the stool age effect). By doing so, the effects of coppicing and harvesting were also tested. However, this test was not systematically possible at each site.

In order to test for the effects of stem and stool (or root system) ages on inter-annual variations in BAI, one-tail paired t-tests (paired by site and rotation) were performed on the reconstructed annual growth data. We tested whether BAI after one growing season differed from BAI after two seasons, BAI after two growing seasons differed from BAI after three seasons, and BAI after three growing seasons differed from BAI after four seasons. This was

done without considering whether MYP was reached or not. To statically compare annual aboveground biomass yields between sites, estimated yield data had to be produced for each plot within a site (n = 9). Therefore, the average stem diameter area of all the plots in a SRC was used as the denominator to calculate the difference (in %) with the average stem diameter area of each plot. To compute values that reflect MYP, only annual yields of growing seasons that had reached MYP were used to calculate an average annual yield for the SRC. This average annual yield was then multiplied by the percent differences between average stem diameters (i.e. plot vs SRC) to obtain a single annual biomass yield value for each plot of each SRC that reflects MYP. By doing so, it is recognized that the time to reach maximum yield varies depending on the conditions that prevail at a site. It is also representative of soil nutrient availability and global variations of hydroclimatic conditions that impact growth at a site. One-way ANOVA with permutational test was also performed to compare MYP at plot scale between sites.

To compare our ability to estimate aboveground biomass yield using the area of the largest basal diameter as well as other growth variables such as height, root age, stem age, number of rotation and number of stems per stool, we partitioned the variance in biomass as proposed by [41]. This allowed to assess: (1) how much of the variance in biomass yield explained by the area of the largest basal diameter is concomitantly explained by another growth variable and (2) if that other growth variable could explain a part of the variance in biomass yield that is not explained by the area of largest basal diameter. Partitioning was done using the function varpart available in the *vegan* package. Variances that were explained only by the area of the largest basal diameter or only by another growth variables were tested by permutation through partial canonical redundancy analysis. The function rda available in the *vegan* package was used. All statistics described above were done using R 3.01 (R Core Team 2012).

Results

Aboveground biomass yields and maximum potential

A significant relationship was found between the area of the largest stem and aboveground dry biomass (Fig. 2). The intercept of this model was near zero. The linear relationship between the area of the largest stem and dry biomass was also significant with the mixed model ($p < 0.001$, n = 28, results not shown), but site effect (random factor) was not significant ($p = 0.38$). The slope of the linear regression (0.001725) was also similar to that of the mixed model (0.001718). The independence of measurements was therefore assumed and the linear equation in Fig. 2 was used to estimate MYP as explained in the Material and Methods section. Another series of mixed models did not reveal a

10

significant difference between the area of the largest stems measured in 2011 and estimates of area of the largest stems for that same year (p = 0.43, n = 516, results not shown), thus confirming the validity of our method to hindcast aboveground biomass. The significant site effect (random factor) confirms that yields differed between sites.

Figure 3 illustrates growth dynamics of six SRCs that have completed only one rotation, i.e at least four years. The MYP at MTL1 was reached in the second growing season following coppicing (i.e. S2R3), whereas MYP was reached at ABI1 and RXP1 in the third growing season following coppicing (i.e. S3R4). Coppicing was not done at SJPJ1, but MYP was also reached in the third growing season (i.e. S3R3). At LAV1, MYP was reached in the second growing season (i.e. S2R4). For this SRC, because coppicing was performed after the second growing season, it is not possible to know if MYP could have been reached in a shorter time. Also, annual yields did not decrease after seven years of growth at that site (i.e. S7R9). At least two full rotations were completed at BOI1, HTG1 and STR1. The MYP for these SRCs was reached in the second growing season following coppicing (i.e. S2R6, S2R12 and S2R6, respectively, Fig. 4).

On average, MYP estimates at MTL1, STR1 and ABI1 were significantly lower than all other sites (i.e. 7.0, 10.1 and 10.4 t ha^{-1} year^{-1}, respectively), whereas SJPJ1and HTG1 had the highest MYP estimates (i.e. respectively 23.8 and 21.1 t ha^{-1} year^{-1}) (Fig. 5). The MYP estimates at ALB1 and RXP1 (i.e. respectively 20.5 and 18.5 t ha^{-1} year^{-1}) were significantly higher than those at BOI1 and LAV1 (i.e. 14.3 and 13.2 t ha^{-1} year^{-1}, respectively) (Fig. 5).

Basal area increments were significantly lower after one growing season compared to the second growing season when grouped and compared by site (model 1, Table 3), but no significant effect was found when comparing the second and third growing seasons, or comparing the third and fourth growing seasons (respectively models 2 and 3, Table 3).

Partitioning of the variance in aboveground biomass biomass

Partitioning of the variance showed that the area of the largest diameter was the most robust proxy to explain aboveground biomass (Table 4). Height shared 0.81 of the adjusted R^2 with the area of the largest diameter, and it added 0.03 (p < 0.05) to the adjusted R^2, meaning that 3% of the variance was not explained by the effect of the area of the largest diameter. The highest adjusted R^2 (0.90) was obtained by combining the number of rotations to the area

of the largest diameter. The adjusted R^2 was not improved by combining either root age, stem age or the number of stems per stool to the area of the largest diameter.

Relationships between growth variables and stem/root ages

Mixed model analysis showed that area of the largest diameter-to-height ratio significantly increased with the number of growing seasons, whereas site effect (random effect) was not significant (model 1, Table 5). This ratio changed most dramatically from the first growing season to the second growing season. The major part of the variance could also be explained with a binary variable representing the first and subsequent growing seasons (model 2, Table 5). Site effect was significant in this second model. This means that most of the variation in area of the largest diameter-to-height ratios explained by the mixed models is due to changes occurring during the first two growing seasons.

Growth differences following coppicing

Based on data from SJPJ2 and BOI2, coppicing performed respectively after one and two growing seasons resulted in large increases in the area of the largest diameter and aboveground biomass (Table 6). At the RXP site, a comparison between three SRCs suggests that coppicing increased the area of the largest diameter and aboveground biomass yield after two growing seasons within the first rotation. Coppicing performed after the second growing season at the STR site had no effect on area of the largest diameter or biomass yields.

Growth differences between rotations and stool ages

At the ABI site, a clear rotation effect was observed. Area of the largest diameter at the end of the first and second growing seasons respectively increased by 87% and 130% between the first and second rotations (i.e. S1R2 vs S1R5, and S2R3 vs S2R6, Table 7). At SJPJ1 where coppice was not done, area of the largest diameter at the end of the first growing season did not change significantly between the first and second rotations, but area of the largest diameter at the end of the second growing season (the coppice year) increased by 66% between the first and second rotations (i.e. S1R1 vs S1R, and S2R2 vs S2R5, Table 7). In contrast, at both RXP1 and MTL1, shifting from the first rotation to the second rotation did not significantly increase the area of the largest diameter at the end of the first growing season (i.e. S1R2 vs S1R5), and at MTL1 after the second growing season (i.e. S2R6, Table 7). A special

12

case to study the effects of rotation on biomass yields is HTG1 because four full rotations are accounted for. No specific trend was observed at HTG1 in terms of rotation effect. Even if area of the largest diameter of the first rotation was lower than the second rotation, the number of stems per stool in the second rotation was higher (results not shown), which explains the higher yield observed after the first growing season of the second rotation compare to the first rotation (i.e S1R2 vs S1R5, Table 7). The third rotation was likely among the least productive. After four rotations at the HGT site, yields remained very high (Fig. 4).

At the BOI site, at the end of the first growing season, the area of the largest diameter was 38% higher on three year-old stools than on five year-old stools (Table 7). However, this difference decreased over time to 34% at the end of the second growing season and to 26% at the end of the third growing season (Table 7). Similarly, differences of area of the largest diameter at HTG1 decreased over the growing seasons when comparing the four rotations. Whether the differences were positive (i.e. first vs. third rotations, first vs. fourth, second vs. third and third vs. fourth) or negative (i.e. first vs. second rotations), the differences were: (1) much larger when comparing the first year of growth to other growth years, and (2) dramatically lower when only older stems were compared. At SJPJ1, however, no significant difference was found at the end of the first growing season, although it was strongly significant at the end of the second growing season, probably because MYP was already reached in the second rotation. Also, at STR site, while no significant difference was found at the end of the second growing seasons between the first and second rotations, area of the largest diameter and biomass yield at the end of three growing seasons decreased significantly (Table 7).

Discussion

Estimation of aboveground biomass yields

Several non-destructive allometric models to estimate S*alix* spp. aboveground biomass using various measurements of living stems as input variables have been developed [42-44, 45, 46]. The positive relationship between stem diameter and aboveground biomass is normally expressed by an exponential function [47, 15]. The predictive power of these models is generally greater (i.e. up to $R^2 = 0.99$) than that of the model used in this study to calculate annual aboveground biomass yields. The difference is likely due to the fact that we considered only the main stem from each stool in our calculations, whereas most other models integrate all stems from a given stool. At HTG1, for example, the sum of basal areas of all living stems from each stool (M. Labrecque, unpublished data) was strongly

13

related to aboveground biomass ($R^2 = 0.85$, data not shown), whereas the area of the largest diameter was more weakly related to biomass ($R^2 = 0.45$, data not shown). It should be noted that modeling aboveground biomass yield with the area of the largest diameter instead of the largest diameter alone has linearized the relationship, most likely because area is more representative of biomass accumulation than diameter [48]. Similarly, allometric models to estimate aboveground biomass are often based on linearized diameter with log transformation, second order polynomial of diameter or the area of cross sections [49, 10, 44, 42].

Pearson correlation coefficients between the area of the largest diameter and aboveground biomass yield varied strongly within each site (Table 1). Biomass yield was correlated with the area of the largest diameter, but several coefficients were low. Again at HTG1, for example, the coefficient of correlation was 0.67 using data of the first growing season and rotation following coppicing, whereas it was 0.35 using data of the first growing season but of the second rotation, which was characterized by a high number of stems per stool (Table 1). To obtain a high fit between stem diameter and aboveground biomass, Sevel et al. [50] argued that a model must be site-specific and it must ideally be developed from yearly data to fully account for carbon allocation in aboveground components. Conversely, Arevalo et al. [42] reported that, despite aboveground biomass being strongly influenced by site and climatic conditions, relatively robust regression models between stem diameter and biomass can be developed at the landscape scale. These authors stated that even if some accuracy is lost, the approach of measuring stem diameter only overcomes the limitation imposed by the energy (time and effort) and cost required to build allometric models specific to the sites and years. Our results corroborate this latter conclusion. This is likely because area of the largest diameter is the consequence of maximum growth of all stems of the stool, while it is also a large part of aboveground biomass. The use of the general linear function (Fig. 2) to estimate aboveground biomass production is therefore rationalized for three main reasons: (1) it has a high R^2, (2) its intercept falls very close to the origin, and (3) the large differences in measured total biomass (after three growing seasons) between sites and the non-significant site effect when it is considered as a random factor warrant that the model is suitable to estimate and compare annual aboveground biomass production between sites.

A additional part of the residuals in aboveground biomass was explained by the height and the number of rotations (i.e. 3% and 4%, respectively), but the area of the largest diameter remained the variable which best explained the variance in biomass (Table 4). Across sites, the variance in aboveground biomass was not explained by the number of stems per stool, probably because the biomass of SX67 is allocated in a few large stems and especially

14

in the largest stem (M. Fontana, personal observation). For the first growing season, the number of stems per stool was significantly explained by the age of the root system (Table 5), but all the variance in aboveground biomass explained by root age was captured by the area of the largest diamter (Table 4). The residuals of the models in Table 4 likely mean that some factors influencing biomass yields and specific to site, growing season and wood quality (e.g. density) were not captured from our measurements. For example, HTG1 was the only case for which the area of the largest diameter of the first growing season decreased (i.e. between the first and second rotation), whereas aboveground biomass increased (i.e. S1R2 vs S1R5, Table 7). This was due to a concomitant increase in height and number of stems per stool by 21% (p < 0.01) and 270% (p < 0.001), respectively (results not shown). As a whole, however, our approach of using the area of the largest diameter to estimate aboveground biomass holds quite well for SX67 across the network, as indicated by the partitioning of the variance in biomass.

Soil and climatic variation encompassed by our SRC network (Table 2) clearly had a large impact on aboveground biomass yields (Figs 3 to 5). The range of our MYP estimates (i.e. from 7 to 23.8 t ha^{-1} year^{-1}, Fig. 5) roughly covers values reported in the literature for SRC of *Salix spp.* under temperate climates. For example, a similar range of biomass yields was reported for *S. viminalis* in northern Europe, i.e. from 10 t ha^{-1} yr^{-1} [15] to 25 t ha^{-1} yr^{-1} [51]. In Canada, productivity of *S. miyabeana* was reported as dramatically low (i.e. 1.2 t ha^{-1} yr^{-1} for a rotation of four years) in the dry Canadian Prairies [19] or as very high (i.e. beyond 25 t ha^{-1} year^{-1}) on loamy clay soils under a wetter and relatively warmer climate in southern Quebec [3].

At HTG1, by the time it was in its fourth rotation, the stools had merged and thus, the shrubs could not be easily differentiated in the field. The number of stems per surface area was not monitored, but it appeared similar to the other sites. However, since a stool density of 18,500 per ha was used to estimate biomass yields, it is likely that the bias (i.e. systematic overestimation) is larger for HTG1 than for the other sites. Similarly at MTL1, the shrub density was strongly overestimated because a significant ground competition resulted in strong mortality within micro-sites (for which measurements were not performed). Thus, we believe that the yield estimate for this SRC is representative only for healthy shrubs without competition. A rapid visual assessment of mortality led to the conclusion that mortality was low for all other sites. Comparatively, the mortality of SRCs of *S. viminalis* and *S. discolor* in southern Quebec has been estimated at less than 10% at the end of first rotation, with about 20,000 cuttings per hectare [9].

Effect of coppicing on growth and yield

After the first or second growing seasons following willow establishment, it is customary to coppice. In this study, the effects of coppicing have been tested for the first growing season at BOI2 and SJPJ2 and for the second growing season at the RXP and STR sites (Table 6). The benefits of coppicing were obvious at sites where soil CEC was 12 $cmol_c$ kg^{-1} or over, i.e. the organic soil at the RXP site or the mineral soil with significant silt and clay at BOI2 and SJPJ2 (Table 2), favoring major increases in the area of the largest diameter and aboveground biomass yield. Conversely, no gain from coppicing was detected at the STR site as the sandy loam soil is characterized by a low CEC (7 $cmol_c$ kg^{-1}) that supports low yields. It could also be that other factors such as lower water availability due to the coarser soil texture at the STR site (sandy loam at STR compared to loam or organic soil elsewhere) may be influencing growth patterns. We could not directly validate our inference on the influence of coppicing for the other SRCs supported by sandy soils, i.e. MTL and LAV, because comparison of the area of the largest stems and of the aboveground biomass yields before and after coppicing was not possible. However, the SRCs at the LAV site allowed for an indirect assessment of the effect of coppicing on stem diameter. Both LAV2 and LAV1 were established in 2005, but coppicing was performed after one and two growing seasons, respectively. The areas of two year-old stems with the largest diameters at LAV2 (in 2007, S2R3) were 17% higher ($P < 0.05$, results not shown) than the areas of the largest diameters of two-year old stems at LAV1 (in 2008, S2R4). This is likely because the growing conditions of the two years following coppicing at LAV2, i.e. 2006 and 2007, favored slightly higher aboveground biomass yields compared to those following coppicing at LAV1, i.e. 2007 and 2008. Because the stems with two growing seasons were measured at LAV2 on stools that were three years and that stems of the same age at LAV1 were measured on stools that were four years, the slightly larger two-year old stems at LAV2 compared to LAV1 suggests that the growth of the largest stem was not limited at LAV2. In turn, MYP at LAV2 could also be reached during the third growing season after establishment. At the LAV site, we speculate that root development did not limit aboveground productivity after two growing seasons as we have no data on roots to support this.

Our findings therefore corroborate previous studies showing a beneficial effect of coppicing on yields of willow shrubs with a young root system when it is supported by a soil that has a relatively high CEC (e.g. clay to loam or organic as exemplified by the RXP site) and that only small effects of coppicing on yields are expected in the case of soils with coarse texture (e.g. sand) [28]. Crow, Houston [27] showed that the development of the root system is highly influenced by harvesting, suggesting that coppicing concomitantly limits the maximum root and

16

stem diameters. They tested the rotation length of the harvest and did not report any significant difference in the number of fine roots (i.e. < 2 mm). Based on our data, it is possible that the yield benefits of extending the length of the first rotation by one year (i.e. four years without any coppice) are larger than introducing coppicing and shortening the length of the rotation by one year (i.e. the coppice year combined with the following 3 years). However, it is impossible to fully assess if there were any benefits based on our data.

Effect of stem age across rotations

Within one rotation, our results suggest a significant increase in BAI only between the first and second growing seasons, independently of the number of rotations, but not between the second and the third, nor between the third and the fourth growing seasons (models 1, 2 and 3, Table 3). Such observations were also made in other SRCs within the first rotation [8, 51]. A high bark-to-wood ratio for small diameter stems (i.e. under 20 mm) suggests a mass-relative high nutrient requirement in aboveground biomass during the first growing season compared to the following growing seasons [52]. Furthermore, resprouting of willow stems suggests a strong demand on carbon reserves until stems contain enough mature leaves to reach energy independence – starch reserves in roots are used after coppicing for initial stem growth [53]. Therefore, the low productivity of SX67 during the first growing season appears to be a physiological trait that other willow cultivars possess.

At HTG1 and BOI1, the differences in the area of the largest diameter between stems of the same age (i.e. comparing the first rotation to the second rotation) have systematically decreased with stem age (years 1, 2 and 3, Table 7). The growth difference between stems with one growing season (i.e. between the first two rotations) was particularly high. Carbon allocation was probably more evenly balanced between the stems within the first growing season after coppicing, while some stems began to dominate and others died out in the following growing seasons [54]. Consequently, the area of the largest diameter-to-height ratio decreased dramatically between the first and subsequent growing seasons (model 2, Table 3). This response was also site-specific. The increase in aboveground biomass in the first growing season compared to the following ones in the first rotation was larger than the increase in the first growing season compared to the following ones in the second rotation (Figs 3 and 4). However, shade is dramatically decreased after coppicing and in turn, strong weed regrowth can increase competition for resources (light, water and nutrients) [55]. Additionnally, root:shoot ratio can suddenly increase following coppicing, which require a strong carbon cost for root respiration compared to subsequent growing seasons [56]. Total yield was,

17

however, generally higher during the second rotation (see section below) because, in part, the productivity after the first growing season in the second rotation was greater than that of the first rotation. This also suggests that the productivity of the first growing season of the first rotation is not optimal because of an under-developed rooting system.

Delays in reaching maximum yields

Kopp et al. [39] reported that coppicing stems for ten consecutive years resulted in asymptotic increases in aboveground biomass and reached maximum values after two to three growing seasons in fertilized plots and after four to five growing seasons in non-fertilized plots. A similar lag effect to reach MYP was also apparent for our sites. Our study generally highlights that MYP could be reached after two to three growing seasons after SX67 was coppiced and this variation also seems to depend on soil texture. The sandiest sites (i.e. LAV, MTL and STR) reached MYP faster than the clay site at ABI (Figs 3 and 4). For example, MYP at MTL1 was reached two years after coppicing or three years after SX67 establishment (i.e. S2R3). Conversely, soil compaction from extensive cultivation was exacerbated by the high clay content at ABI (Fontana, unpublished data). The time to reach MYP at that site was extended to three years after coppicing or four years after SX67 establishment (i.e. S3R4, Fig. 3). The soils at the remaining sites were from loam to silty clay loam, excluding RXP which was dominantly organic. Their MYP were either reached after the third or the fourth growing season following SX67 establishment. Considering that SX67 in MTL1 and SJPJ1 is respectively the least and among the most productive and that MYP was reached at both SRCs three years after SX67 establishment (i.e. S2R3 and S3R3, respectively), the time to reach MYP appears independent of its magnitude.

As a whole, soil nutrient and water availability as well as soil physical properties are likely conditioning the dynamics of early willow growth and, in turn, the point in time at which a SRC reaches MYP. Based on our data, strong interactions with coppicing, stool establishment and soil texture are apparent. The time needed to reach MYP also appears to have an impact on yields over the various rotations. Kopp et al. [57] argued that fertilization did not increase MYP, but rather decreased the time to reach MYP. On the contrary, N fertilization was reported to increase MYP, especially on acidic sandy soils [29]. Kopp et al. [57] conducted their study on relatively productive agricultural soils so that plant nutrition was likely not a factor limiting growth. Fertilization had an impact on MYP,

18

but it shortened the time needed to reach it, probably because the optimal availability of nutrients decreased the need for early root development [17].

Effect of rotation on yields

Lower aboveground yields for the first rotation compared to subsequent rotations were frequently [10] but not systematically observed [58, 59]. This pattern appears to be true on clayey soils at ABI and HTG, but does not seem to apply at BOI, STR or MTL where SX67 is supported by coarser soils (Fig. 3, Tables 2 and 7). At SJPJ1 and the ABI site, the area of the largest diameter of the second rotation was larger than that of the first rotation (Fig. 3, Table 7), probably due to the delay in reaching MYP. Within site, Larsen et al. [60] found that aboveground biomass yields of the second rotation were quite homogeneous, independently of the large differences in yields observed for the first rotation due to the use of various methods for establishing and harvesting the SRC. This suggests that the increase in yields between the first two rotations is dependent of the yield of the first rotation.

Again at SJPJ1 and the ABI site, we speculate that a more established stool, which can access the soil resources more effectively, explains the lower estimated annual yields of the first rotation compared to those of the second rotation (Fig. 3). In southern Sweden, an analysis carried out on more than 2,000 SRCs of willows indicated a significant increase in yields from the first to the second rotation [23]. However, this study did not report a significant increase in yields from the second to the third rotation. Likewise, Labrecque and Teodorescu [9] found that omitting to coppice *S. viminalis* and *S. discolor* led to a strong gain in yields between the first and second rotations. The differences in yields from the first to the second rotation could likely have been reduced if coppicing had been conducted because it would possibly have allowed to reach the MYP one year earlier.

The estimated annual aboveground yield at LAV1 did not decrease after seven growing seasons (i.e. S7R9), nor did it decrease at HTG1 after four rotations with stools of fourteen years (i.e. S4R14, Figs 3 and 4). In fact, the largest diameters in the fourth rotation at HTG1 were higher than those of the previous rotations (Table 7). This is in full agreement with Volk et al. [24] who reported some increases in yields between the first and second rotations (23%) and also between the first and fourth rotations (30.8%) for trials established on well-drained gravelly silt loam soils. However, the third rotation at HTG1 was among the least productive (Table 7). For nine willow cultivars, including SX67, Guidi Nissim et al. [3] observed a higher annualized aboveground biomass production when accounting for a second rotation of four years compared to a first rotation or a third rotation of three years.

19

Divergence was particularly large between the first and second rotations. Differences in annual biomass production could also be due to the fact that the first year is generally less productive than the second or third growing seasons, especially during the first rotation [61], and that adding a fourth productive growing season tends to increase the overall biomass production on an annualized basis. This observation is consistent with our findings because the SRCs with a fourth growing season were among the most productive (S4R5 for ABI1, S4R5 for ALB1, S4R8 for BOI1, S4R14 for HTG1, S4R6 for LAV1, S4R5 for MTL1 and S4R5 for RXP1, Figs 3 and 4).

Conclusion

Growth dynamics of SX67 was investigated as a function of stool age, coppicing and soil properties. Over the growing seasons, an asymptotic increase in annual aboveground yield is generally assumed until reaching maximum yields. The delay required to reach optimal annual yield affects the difference in aboveground biomass yields between the first two rotations. Growth dynamics also strongly varied depending on site (soil) characteristics. Heavy clay soils restricted stool establishment. On compacted clayey soils, a lag of three years after coppicing was needed to reach maximum yields. At the sandiest sites, the delay to attain maximum yield was shortened to only two growing seasons after SX67 was coppiced, suggesting less constraining conditions for stool establishment. At sites where soils have a higher silt content (sandy loam or loam), the growth dynamics is expected to be somewhere between these two cases and the maximum yields can be high. In all soil types, aboveground biomass yields of the first growing season remained lower than subsequent growing seasons, especially during the first rotation. The difference was exacerbated at sites where soils restrict stool establishment (e.g. clayey soil with a plough pan). Our results do not support the idea that coppicing of SX67 should be performed for the sites that we tested with coarser soils because the positive effects on stem growth were negligible or inexistent, whereas productivity of stems growing on clayey soils was largely improved after coppicing. However, our data did not allow to test if total aboveground biomass yield was higher when combining the coppice year and the following three years of growth compared to a full four year rotation without coppicing. In the case that total aboveground biomass yield would be stronger by including coppicing, it would be valuable to perform the balance between the carbon gained by coppicing and the carbon cost to perform it.

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20

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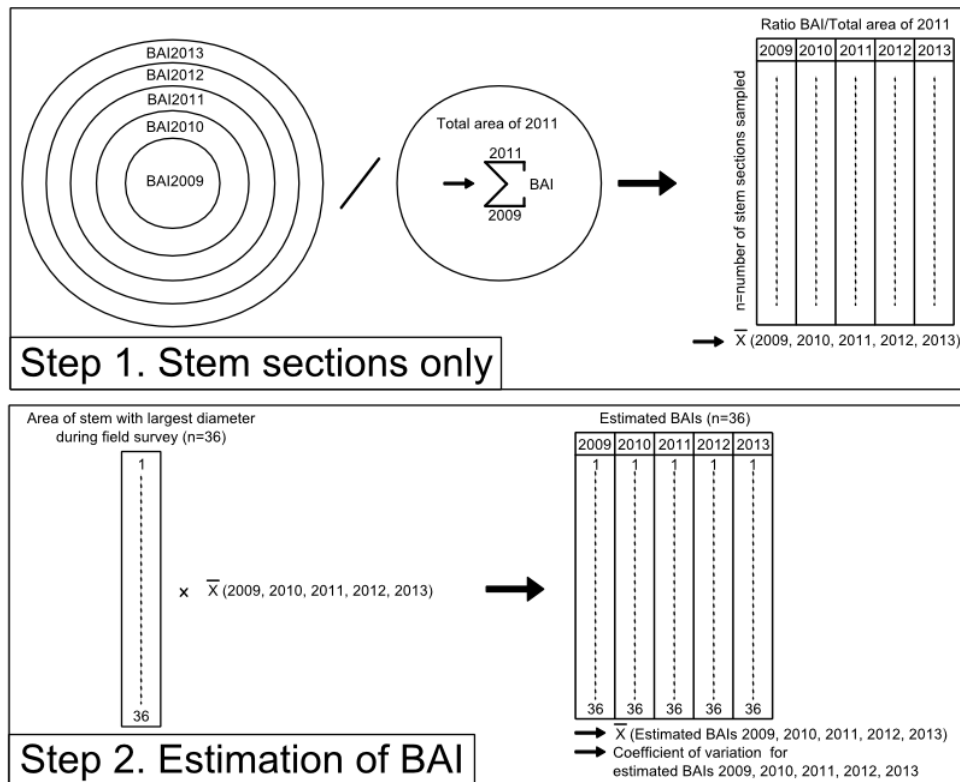
Fig. 1 Method to estimate the basal area increments (BAI) of all growing seasons captured within the sampling of a short rotation culture of SX67.
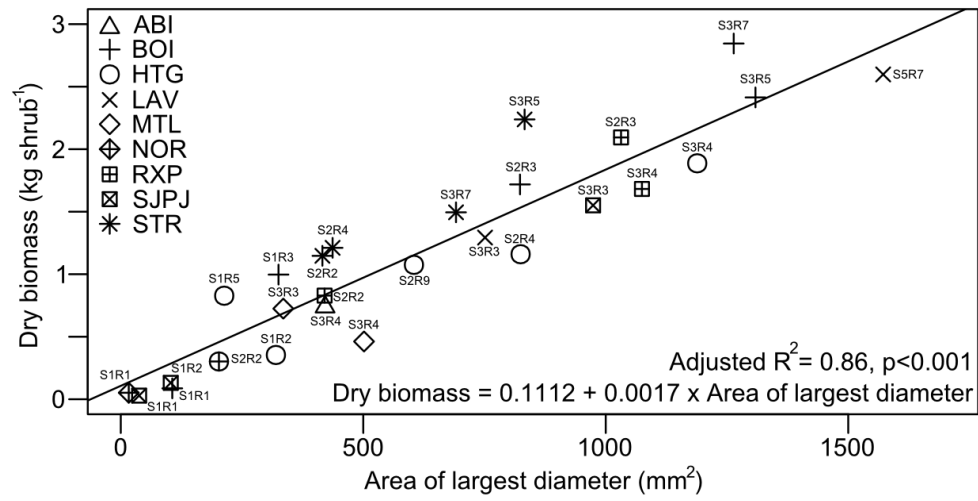
Fig. 2 Linear regression model between the diameter measured on the largest stem and dry aboveground biomass of shrubs. Each data point refers to an average of 24 to 36 shrubs. A different symbol is attributed for each site. Data labels indicate the number of growing seasons of the stems (S) and roots (R). For example, the label S1R5 means a one year-old stem and a five year-old root system.
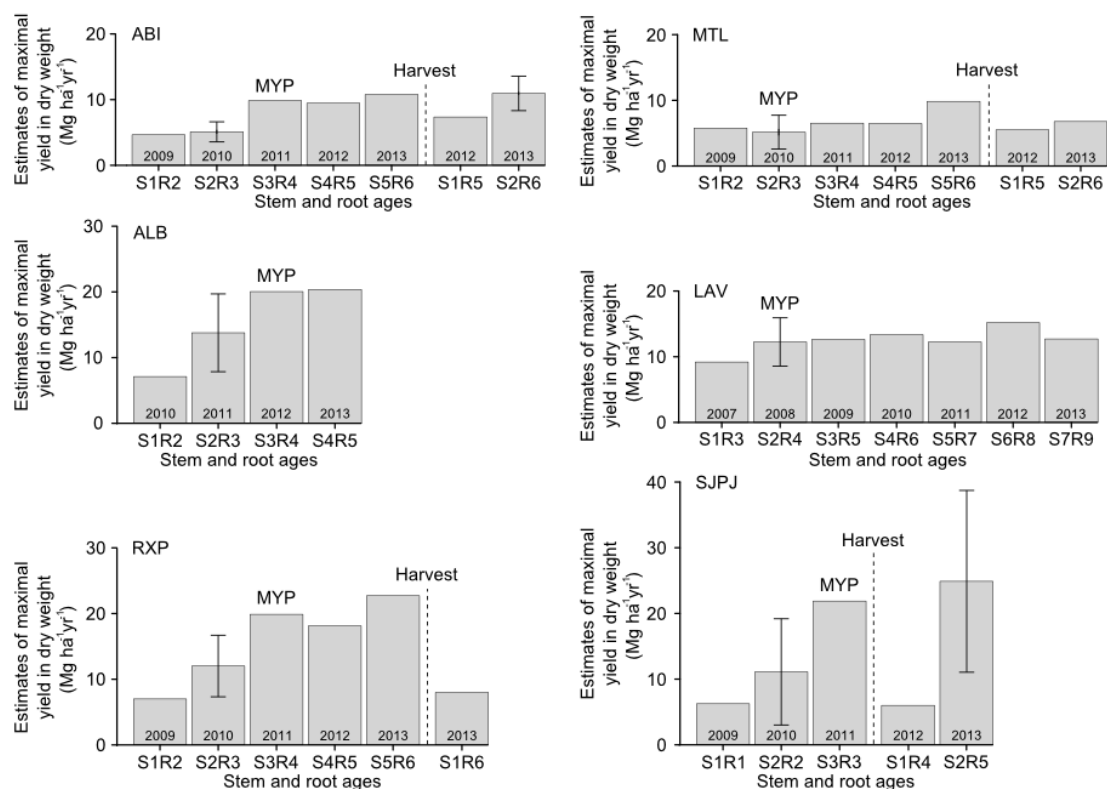
Fig. 3 Estimated annual aboveground biomass yields of the six short rotation cultures of SX67 that have completed only one rotation (i.e. at least four years). The values correspond to slight overestimations of actual yields because mortality was not taken into account. The root age and the stem age are identified in a single descriptor (i.e. SaRa where S is stem, R is root and a is age of the stem and root system). Error bars (standard deviation) were centered on the second growing season to illustrate the year that maximum yield potential (MYP) was reached, which is indicated over the bar of the appropriate year.
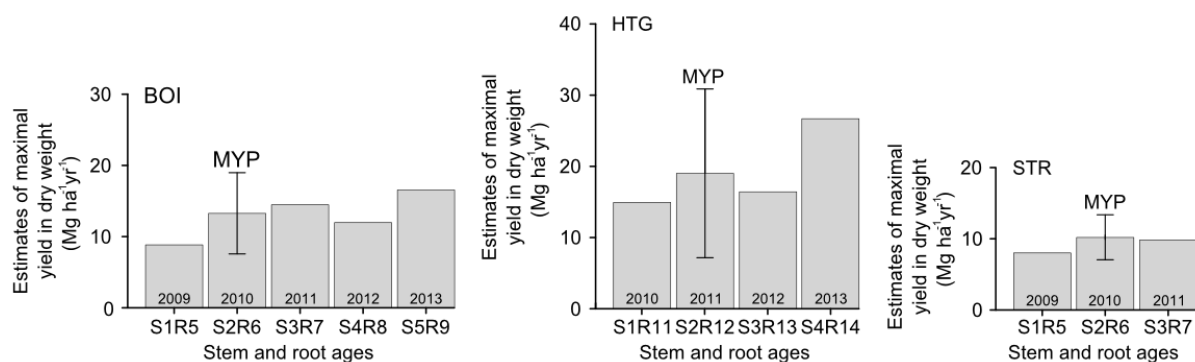
Fig. 4 Estimated annual aboveground biomass yields of the last rotation in three short rotation cultures of willow that have completed at least two rotations. The values correspond to slight overestimations of actual yields because mortality was not taken into account. The root age and the stem age are identified in a single descriptor (i.e. SaRa where S is stem, R is root and a is age of the stem and root system). Error bars (standard deviation) were centered on the growing season for which the diameter of the largest stem was measured. The year that maximum yield potential (MYP) was reached is indicated over the bar of the appropriate year.
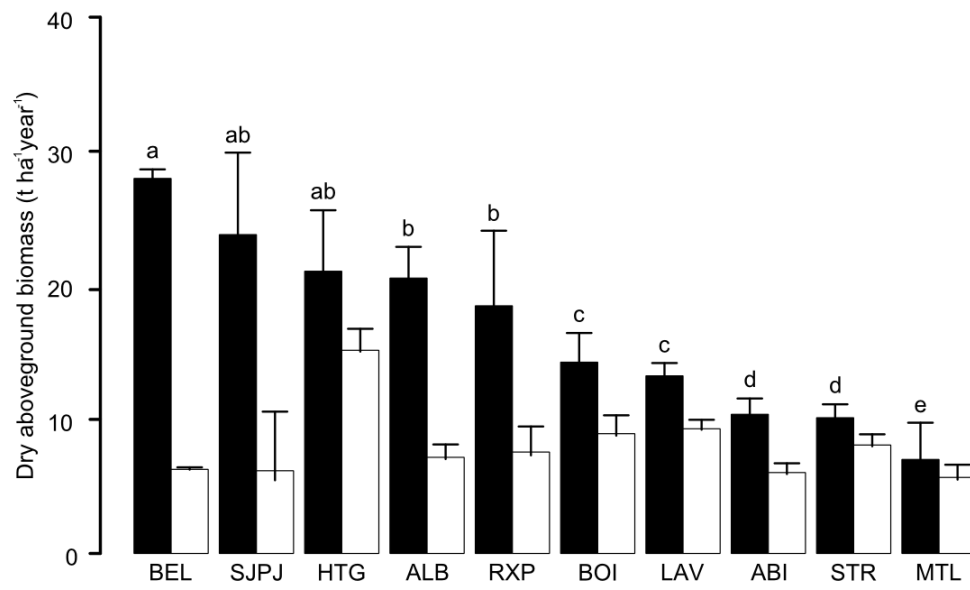
Fig. 5 Mean maximum yield potential (MYP, black bars) and annual aboveground biomass yield of the first growing season (white bars) for each site. In the case where there is no significant difference in MYP between sites (permutational ANOVA), the same letter is assigned.

Table 1 Mean diameter (D) and height (H) of the stems and number of stems per stool measured in the short largest rotation cultures (SRC) of SX67. Aboveground biomass yield, the years for which dendrochronolgy estimations were performed and Pearson correlation coefficient between the area of the largest diameter and aboveground biomass dry weight (r_p A:W) are reported when available.

Site	SRC	Year established	Soil sampling year	Rotation	Stem and stool ages	Field measurement year (biomass)	n	D (mm)	H (m)	Number of stems per stool	Measured yield (t ha-1)	Years that yields were estimated	rp A:W
Abitibi	ABI1	2008	2011	1	S3R4	2011	36	23.2	2.9	10.8	14.0	2009 to 2013	0.45
	ABI2	2008	2011	2	S2R6	2013	36	23.9	NA	NA	NA	2011 to 2013	NA
Albanel	ALB1	2009	2013	1	S4R5	2013	50	46.5	5.2	2.5	NA	2010 to 2013	NA
	BOI1	2005	2011	2	S3R7	2011	36	34.8	5.4	2.6	38.5	2009 to 2013	0.77
Boisbriand					S3R5	2011‡	36	40.8	5.3	5.1	44.7	No	0.57
	BOI2	2007	NA	1	S2R4	2010‡	36	32.4	4.9	5.5	31.8	No	0.20
					S1R3	2009‡	36	20.4	3.5	8.5	19.1	No	0.30
					S1R1	2007	36	11.6	1.9	3	2.9	No	0.69
				4	S3R13	2012	36	43.7	5.5	NA	NA	2010 to 2013	NA
				3	S4R11	2009	24	50.0	6.8	5.2	NA	No	NA
					S2R9	2007	24	27.8	4.8	4.6	19.9	No	0.41
					S3R7	2005	24	34.0	4.5	6.5	NA	No	NA
Huntingdon	HTG1	2000	2012	2	S2R6	2004	24	27.5	4.0	12.1	NA	No	NA
					S1R5	2003	24	16.5	2.9	11.3	15.3	No	0.35
					S3R4	2002	24	38.9	4.4	3	34.9	No	0.76
				1	S2R3	2001	24	32.4	3.7	3	21.5	No	0.81
					S1R2	2000	32	20.2	2.4	4.2	6.5	No	0.67
Laval	LAV1	2005	2011	1	S5R7	2011‡	36	44.8	6.4	2.1	46.8	2007 to 2013	0.78
	LAV2	2005	NA	1	S2R3	2007	36	30.9	4.8	5.4	23.9	No	0.60
Mont-Laurier	MTL1	2008	2011	1	S3R4	2011	36	25.3	3.2	2.8	8.4	2009 to 2013	0.79
				2	S2R6	2013	16	18.5	NA	NA	NA	2011 to 2013	NA
	RXP1	2008	2011	1	S3R4	2011	36	36.3	4.6	NA	30.3	2009 to 2013	NA
Roxton Pond	RXP2	2008	2011	2	S1R6	2013	20	15.3	NA	NA	NA	2013	NA
	RXP3	2006	No	1	S2R3	2008	36	36.3	5.1	3.1	38.7	No	0.40
	RXP4	2006	No	1	S2R2	2007†	36	23.1	3.5	9.0	15.3	No	0.29
	SJPJ1	2009	2011	2	S2R5	2013	50	33.0	NA	NA	NA	2009 to 2013	NA
Saint-Jean-Port-Joli				1	S3R3	2011†	36	35.2	4.2	2.7	27.9		0.83
	SJPJ2	2006	NA	1	S1R2	2007	36	11.5	2.0	10.9	4.3	No	0.48
					S1R1	2006†	36	6.9	1.4	2.6	1.0	No	0.18
Saint-Roch-de-l'Achigan	STR1	2005	2011	2	S3R7	2011	36	29.7	4.2	7.6	26.9	2009 to 2011	0.45
	STR2	2007	NA	1	S3R5	2011‡	36	32.6	4.4	3.5	41.4	No	0.71
					S2R4	2010‡	36	23.6	3.7	5.3	22.4	No	0.25

	STR3	2006	NA	1	S2R2	2007†	36	23.0	3.0	7.8	21.2	No	0.44
Mont-Laurier	MTL2	2006	NA	1	S3R3	2008	36	20.7	3.2	3.4	13.0	No	0.57
			NA		S2R2	2007†	36	16.1	2.5	3.1	5.4	No	0.73
Normandin	NOR1	2007	NA	1	S1R1	2007†	36	4.6	0.7	3.6	0.9	No	0.80

An ID is attributed to each SRC to distinguish them between and within sites. The column entitled Rotation and Measurement year indicate respectively the number of rotations of the SRC and the year for which growth variables were measured. The number of shrubs measured within each SRC is also indicated (n). SRCs were coppiced after one growing season, unless otherwise indicated;

† Indicates a SRC which was not coppiced;

‡ Indicates a SRC which was coppiced after two growing seasons.

The shaded area indicates SRCs that were only used to build the model presented in Figure 2

Table 2 Previous land use and general climatic and soil properties of the short rotation cultures of SX67 for which maximum yield potential was estimated.

Site	Latitude	Longitude	Soil type/Previous land use	Soil preparation	First growing season‡	Annual rainfall (mm)	Annual degree days (5°C)	Sand	Clay	O.M.	pH	CEC† (cmol$_c$ kg^{-1})
									—— (% mass) ——			
Abitibi (ABI1 and ABI2)	48.65852	-77.635812	Clay / agriculture	Tillage	2009, 2012$^£$	718	1609	20.6	43.1	7.9	5.6	15.4
Albanel (ALB1)	48.871624	-72.425107	Silt loam / agriculture	Tillage	2010	664	1676	32.2	9.6	10.2	6.2	18.8
Boisbriand (BOI1)	45.629525	-73.89309	Loam / hardwood forest	No till	2006, 2009	762	2368	34.9	18.9	9.2	7.5	23.7
Huntingdon (HTG1)	45.144667	-74.142097	Silty clay loam / agriculture	Tillage	2001, 2003, 2006, 2010	765	2414	18.9	27.6	11.2	7.3	38.1
Laval (LAV1)	45.553382	-73.833063	(Sandy) loam / agriculture	Tillage	2007	717	2488	49.6	11.3	5.4	5.3	6.3
Mont Laurier (MTL1)	46.455658	-75.498268	Loamy sand / mixed forest	Tillage	2009, 2012	699	2027	74.1	3.7	6.9	5.2	3.4
Roxton Pond (RXP1 and RXP2)	45.558663	-72.676412	Organic / agriculture	Tillage	2009	864	2333	46.2	5.7	67.6	5.5	68.1
Saint-Jean-Port-Joli (SJPJ1)	47.246119	-70.227056	Loam / forage	No till	2009, 2012	748	1867	30.7	22.9	9.1	5.3	12.2
Saint-Roch de l'Achigan (STR1)	45.844108	-73.632014	Sandy loam / agriculture	Tillage	2006, 2009	831	2288	59.2	8.7	4.6	5.6	7.0

‡ Multiple years indicate multiple rotations; †CEC is effective cation exchange capacity; £Only for ABI2.
O.M. refers to organic matter content measured by loss on ignition using a muffle furnace

Table 3 Results of statistical differences in basal area increment between growing seasons (GS).

Model	Tested groups	P value
1	GS1 < GS2 (n = 26)	0.002
2	GS2 < GS3 (n = 14)	0.361
3	GS3 < GS4 (n = 14)	0.201

Groups were tested using a permutational one tailed paired t-test.

Table 4 Partitioning of the variance of dry aboveground biomass between the area of the largest diameter and a second explanatory growth variable (i.e. height, root age, stem age, rotation number or number of stems per stool).

Model	n	Adj. R^2 of the area of largest diameter ℂ second explanatory variable	Adj. R^2 of the area of largest diameter ∩ second explanatory variable	Adj. R^2 of the second explanatory variable ℂ Area of largest diameter	Adj. R^2
1	27	0.05[**]	Height		0.89
			0.81	0.03[*]	
2	27	0.49[**]	Root age		0.86
			0.38	0.00 NS	
3	27	0.37[**]	Stem age		0.86
			0.49	0.00 NS	
4	27	0.73[**]	Rotation number		0.90
			0.13	0.04[*]	
5	26	0.86[**]	Shoot number		0.86
			0.00	0.00 NS	

All linear relationships are positive. Models are significant at α <0.05([*]) and <0.01([**]). The column entitled Adj. R^2 of the area of largest diameter ℂ second explanatory variable indicates the adjusted R^2 of the variance explained by the area of the largest diameter which does not overlap the effect of the second explanatory growth variable. The column entitled Adj. R^2 of the area of largest diameter ∩ second explanatory variable indicates the adjusted R^2 of the variance explained by both the area of the largest diameter and the second explanatory growth variable. The column entitled Adj. R^2 of the second explanatory variable ℂ Area of largest diameter indicates the adjusted R^2 of the variance explained by the second explanatory growth variable which does not overlap the effect of the area of the largest diameter. The column entitled Adj. R^2 indicates the adjusted R^2 of the variance explained by the cumulative effect of the area of the largest diameter and the second explanatory growth variable.

Table 5 Results of mixed model analysis of the area of the largest diameter-to-height ratios as the response variable, site effect as the random factor and stem age as the fixed variable. Model 1 uses stem age as a continuous variable, whereas model 2 uses it as a binary variable (model 2). Model 3 is a linear regression with the number of stems per stool as the response variable and the age of the root system as the explanatory variable.

Model	n	Response variable	Random factor	Fixed variables	R^2
1	26	Area of largest diameter-to-height ratio	Site NS	Stem age[***]	0.79
2	26	Area of largest diameter-to-height ratio	Site[**]	1st growing season of a harvesting cycle[***]	0.61
3	6†	Number of stems per stool	No	Age of root system[**]	0.54

Models are significant at $\alpha < 0.01$([**]) and < 0.001([***]).

Table 6 Results of statistical differences of the area of the largest stems (A) and aboveground biomass (Yield) measured before and after the stools were coppiced (first rotation only). Differences in aboveground biomass yield of those stools are also reported. The root age and the stem age were identified in a single descriptor (i.e. SaRa where S is site, R is root and a is age of the stem and root system).

SRC(s)	Year of coppicing	n	Stem and stool ages	A	Yield
BOI2	2008	72	S1R1 vs S1R3	+ 192% ***	+ 734% ***
SJPJ2	2006	72	S1R1 vs S1R2	+ 153% ***	+ 691% ***
RXP4 vs. RXP1	Not performed vs 2008	72	S2R2 vs S2R3	+ 23% **	NA
RXP4 vs. RXP3	Not performed vs 2006	72	S2R2 vs S2R3	+ 148% ***	+ 151% ***
STR3 vs. STR2	Not performed vs 2008	72	S2R2 vs S2R4	+ 5% NS	+ 6% NS

Differences (coppicing effect) before and after coppicing were tested by ANOVA with permutational test. Data were always grouped and tested by site or by short rotation culture (SRC). The age of the stems that were compared is indicated in the column Stem age. Models are significant at α <0.01(**) and <0.001(***). An ID is attributed to each SRC to distinguish them between and within sites. The shaded area indicates that the effect of coppicing was tested using the same plots within a SRC, whereas the unshaded area indicates that the effect was tested between different SRCs within a site. At BOI2 and STR2, coppicing was done after two growing seasons, whereas it was done after one year at RXP1, RXP3 and SJPJ2. The number of stools measured is indicated (n).

Table 7 Results of statistical differences of the area of the largest stems (A) measured from stools of the same ages but of different rotations (i.e. different stool ages). Differences in aboveground biomass yield of those stools are also reported. The root age and the stem age were identified in a single descriptor (i.e. SaRa where S is stem, R is root and a is age of the stem and root system)

SRC(s)	Rotation	n	Stem and stool ages	A	Yield
HTG1	1 vs 2	56	S1R2 vs S1R5	- 33%**	+ 134%***
		48	S2R3 vs S2R6	- 29%*	NA
		48	S3R4 vs S3R7	- 23%£	NA
	1 vs 3	48	S2R3 vs S2R9	- 28%*	-7% NS
	1 vs 4	60	S1R2 vs S1R12	+ 37.4 %*	NA
		60	S2R3 vs S2R13	+ 23% NS	NA
		60	S3R4 vs S3R14	+ 29% NS	NA
	2 vs 3	60	S2R4 vs S2R9	+ 2% NS	NA
	2 vs 4	60	S1R5 vs S1R12	+ 107%***	NA
		60	S2R6 vs S2R13	+ 75%**	NA
		60	S3R7 vs S3R14	+ 68%**	NA
	3 vs 4	60	S2R9 vs S2R13	+ 71%**	NA
		74	S4R11 vs S4R15	+ 9%£	NA
MTL1	1 vs 2	52	S1R2 vs S1R5	- 2% NS	NA
		52	S3R3 vs S2R6	+ 2% NS	NA
RXP1	1 vs 2	56	S1R2 vs S1R6	- 4% NS	NA
SJPJ1	1 vs 2	86	S1R1 vs S1R4	- 6% NS	NA
		86	S2R2 vs S2R5	+ 66%***	NA
ABI2 vs. ABI1	1 vs 2	56	S1R2 vs S1R5	+ 87%***	NA
		56	S2R3 vs S2R6	+ 130%***	NA
BOI2 vs. BOI1	1 vs 2	72	S1R3 vs S1R5	- 38%***	NA
		72	S2R4 vs S2R6	-34%***	NA
		72	S3R5 vs S3R7	- 26%**	- 14% NS
STR2 vs. STR1	1 vs 2	72	S2R4 vs S2R6	+ 5% NS	NA
		72	S3R5 vs S3R7	- 16%*	- 31%**

Differences (rotation or harvesting effect) between stools of the same ages but of different rotations were tested by ANOVA with permutational test. Data were always grouped and tested by site or by short rotation culture (SRC). Models are significant at α <0.1(£), <0.05(*), <0.01(**) and <0.001(***). An ID is attributed to each SRC to distinguish them between and within sites. The shaded area indicates that the effect of rotation was tested using the same plots within a SRC, whereas the unshaded area indicates that the effect was tested between different SRCs within a site. The column Rotation indicates the rotations that were compared with ANOVA. The number of stools measured is indicated (n).