Growth and stem quality of hardwood trees planted 18–29 years ago on abandoned farmland following recommended silvicultural practices

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ABSTRACT

The objective of this study is to provide an account of the growth results of valuable hardwood plantations several decades old which have received silvicultural treatments recommended for planting hardwoods on abandoned farmland. Diameter growth and stem quality of sugar maple (*Acer saccharum* Marsh.), black walnut (*Juglans nigra* L.), bur oak (*Quercus macrocarpa* Michx.) and red oak (*Quercus rubra* L.) are analysed. Data were from 15 plantations located in south-western Quebec. The mean annual diameter increments were highest for red oak (0.83 cm yr⁻¹) and black walnut (0.75 cm yr⁻¹), and lowest for bur oak (0.55 cm yr⁻¹) and sugar maple (0.51 cm yr⁻¹). These values are comparable to, or exceed, the best rates in the literature. A mean proportion of 78% to 95% of the first log without defects were produced, depending on the species. Tree mean densities (640 trees/ha) will allow a selection of better stems by thinning. Elite trees have diameters that are 17% to 23% above the average. These results lead us to believe in the potential for the production of quality hardwood timber in plantations in Québec.

Key words: open field plantation, log quality, soil preparation, herbicide application, pruning, thinning, southern Quebec

RÉSUMÉ

L'objectif de l'étude est de rendre compte de la croissance de plantations d'arbres feuillus, vieilles de quelques décennies, ayant reçu des traitements sylvicoles recommandés pour les terres agricoles abandonnées. La croissance en diamètre et la qualité des tiges d'érable à sucre (*Acer saccharum* Marsh.), de noyer noir (*Juglans nigra* L.), de chêne à gros fruits (*Quercus macrocarpa* Michx.) et de chêne rouge (*Quercus rubra* L.) sont analysées. Les données proviennent de quinze plantations localisées au sud-ouest du Québec. Les taux d'accroissement moyens en diamètre ont été les plus élevés pour les chênes rouges (0,83 cm an⁻¹) et les noyers noirs (moyenne 0,75 cm an⁻¹) et plus faibles pour les chênes à gros fruits (0,55 cm an⁻¹) et les érables à sucre (0,51 cm an⁻¹). Ces taux se comparent ou surpassent les meilleurs taux présentés dans la littérature. Une proportion moyenne de 78% à 95% de premières billes sans défauts a été produite. La densité moyenne (640 tiges/ha) permettrait une sélection des meilleures tiges. Le diamètre des arbres élités est de 17% à 23% supérieur à celui de tous les arbres. Ces résultats nous permettent de croire au potentiel de production de bois feuillus de qualité en plantation au Québec.

Mots clés: plantation en champ agricole abandonné, qualité des tiges, préparation des sols, application d'herbicide, taille de formation et d'élague, éclaircie, Sud du Québec

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Introduction

Hardwood planting on abandoned farmland (HPAF) in temperate regions has been the subject of several research investigations that have supported the development of silvicultural practices needed for successful tree survival and growth (Davies 1988; Cogliastro *et al.* 1990; West 2006). Plantation guides were developed based on these results (von Althen 1990; Allen *et al.* 2001; Farlee 2018). Jurisdictions, at various levels, agencies and private organisations, have sometimes developed programs for the promotion and financial support of hardwood plantations on abandoned farmland. However, many hardwood plantations were established without receiving all silvicultural treatments deemed essential to success, and the results obtained

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varied highly and were often disappointing (Stanturf *et al.* 2001; Gardiner *et al.* 2002).

There are few studies that present growth and stem quality results of hardwoods planted two to three decades ago on different sites where basic silvicultural treatments were applied. Hardwood plantation studies more often discuss the effect of silvicultural treatments, often obtained at a single site. Also, hardwood plantation results are rarely about trees with sufficient size to allow evaluation of stem (log) quality. Knowing the likely potential growth range and the expected level of quality of the logs produced in hardwood plantations would be very useful for setting realistic objectives for the production of high value hardwood logs. Such results would also serve the needs of those planning plantations and who are motivated by environmental objectives, such as reducing the impact of intensive agriculture by agroforestry (Bergeron *et al.* 2011; Alam *et al.* 2014), creating forest corridors in highly deforested areas (Saura *et al.* 2017), and capturing CO₂ emissions (Zhang *et al.* 2016). Results that can assist in estimating the growth of hardwood species in plantations on abandoned farmland, and where basic silvicultural treatments are applied, will be useful to such initiatives. The currently available references on hardwood growth generally originate from results obtained in forest environments (Lambert *et al.* 2005) and not from plantations.

The basic silvicultural treatments that are recognized as essential to success in HPAF include initial mechanical or chemical soil preparation, the selection of adapted species using good quality planting material, and planting according to a spacing adequate for the wide rooting system of the trees (von Althen 1990; Gardiner *et al.* 2002). Post-plantation treatments that are recognized as being the most important are the control of herbaceous plant competition by mechanical or chemical means, or by mulching (Cogliastro *et al.* 1990; Truax and Gagnon 1993), and protecting the planted trees from rodents (Ostfeld *et al.* 1997). Early formative pruning, as well as pruning to remove defects, should be applied at various frequencies (Hubert and Courraud 1998). Finally, thinning is also recommended for a constant and relatively rapid stem growth (Bohanek and Groninger 2003).

Diameter growth and the stem quality of sugar maple (*Acer saccharum* Marsh.), black walnut (*Juglans nigra* L.), bur oak (*Quercus macrocarpa* Michx.) and red oak (*Quercus rubra* L.) produced in plantations on abandoned farmland are analysed in this article. The data were obtained from 15 plantations located in south-western Quebec at the northern part of the distribution range of the species under study. However, the low elevation of the area (50 to 97 m a.s.l.) provides a warmer climate than what is found in much of the New England States, just south of the Canada/US border. The objective of this study is to give an account of the results of valuable hardwood plantations, several decades old, which have received the basic silvicultural treatments recommended for planting hardwoods on abandoned farmland. The ranges of growth rates and log quality have the potential to serve as references. We hope that these results encourage the establishment of programs that support investments in hardwood plantation silviculture in order that the majority of planted trees can produce the expected economic and environmental services.

Methods

Study area description

The hardwood plantations analysed are located in the Upper St. Lawrence region of south-western Québec. The plantations are distributed along a 60-km east-west axis, (north to south maximum displacement from this axis is 20 km), thus insuring relatively common climatic conditions. They are also distributed over the two major geological units of the region: dolomitic bedrock (Beekmantown group) in the western section and sandstone (Potsdam group) in the eastern section (Globensky 1987). These two geological units produce significantly different edaphic conditions (Bariteau 1988; Meilleur *et al.* 1994).

The region is characterized by an average frost-free period of 182 days (Huntingdon station, Lat. N: 45° 4' 50", Long. W: 74° 10' 48"). Mean annual temperature is 7.0 °C and monthly mean temperatures of July and January are 21.1 °C and -9.2 °C. Average annual precipitation in rain and snow are respectively 890 mm and 194 mm (MELCC 2010).

Of the 15 plantations analysed, five were established by a forestry consultant within the scope of forestry operations funded by a program to assist forest land owners. This fund was from the Quebec Ministry of Forests, Wildlife and Parks. The other 11 plantations were the initiative of the authors of this article to investigate the effects of various soil preparation treatments, competing vegetation control treatments, or differences in growth among different tree species. Only the trees that received the silvicultural treatments deemed essential are included in the analyses. The results from some of these plantations during their early years of growth have already been published (Cogliastro *et al.* 1997a, 1997b, 2003; Genet *et al.* 2013).

This study focuses on four hardwood species: sugar maple (*Acer saccharum* L.), black walnut (*Juglans nigra* L.), bur oak (*Quercus macrocarpa* Michx.) and red oak (*Quercus rubra* L.). The trees range in age from 16 to 29 years of growth. Some plantations had white ash (*Fraxinus americana* L.) and red ash (*F. pennsylvanica* Marsh.), as well as butternut (*Juglans cinerea* L.), but these species were excluded from the study because of the insect (emerald ash borer) or disease (butternut canker) that affects them at a continental scale. A rapid survey of some these plantations in 2009 revealed an infection/death rate of over 75% of butternuts caused by the butternut canker (D. Gagnon, personal observation). The data for this article were collected from September to December 2016.

Silvicultural treatments

All plantation sites were abandoned from agriculture and were at the herbaceous old-field vegetation stage when they were converted to hardwood plantations. The bare root seedlings (1+0 or 2+0) used were produced by the provincial nursery of Quebec (Berthierville) which has excellent quality criteria. They were all planted manually during the spring (mostly in May). All seedlings received a plastic spiral protector, installed for five years minimum, to protect them from rodent damage.

Table 1 presents data on soil texture, tree species planted and the main silvicultural treatments at each plantation: soil preparation, weed control, deer browsing protection, pruning frequency. For Table 1 onwards, the name

Table 1. Soil texture, hardwood species and silvicultural treatments applied at plantations

Age-Site	Latitude	Longitude	Soil texture	Species present ¹	Soil preparation ²	Post Planting weed control ²	Browsing protection ³	Number of prunings
16-La	45° 3' 51.00"N	74° 16' 34.78"O	stony loam	JUN	(S)P+D	(S)PM	Years 1,2,3	3
17-V	45° 13' 52.99"N	73° 40' 20.99"O	stony loam	JUN	(S)P+D	(S)PM	Year 3	4
18-P	45° 4' 36.77"N	74° 13' 51.97"O	stony loam	QUR-JUN	(S)P+D	(S)PM	nil	4
19-D	45° 3' 2.51"N	74° 5' 37.60"O	sandy loam	JUN	P+D	PM	nil	5
21-D	45° 3' 0.98"N	74° 5' 38.66"O	sandy loam	ACS	H+P+D	PM	nil	5
26-I	45° 1' 36"N	73° 58' 40"O	sandy loam	QUM-QUR-ACS-JUN	NP	H years 1 to 4 + CM	nil	2
26-M	45° 2' 38"N	74° 22' 15"O	sand	QUM-QUR-ACS-JUN	NP	H years 1 to 4 + CM	nil	3
27-Lb	45° 4' 34"N	74° 17' 10"O	stony loam	QUM	NP/P+ D/P+D+Hs	(S)PM/(S) H years 1 to 5	nil	4
27-Lt	45° 2' 18"N	74° 23' 39"O	sand	QUR	P+D	PM	nil	2
27-R	45° 4' 4"N	74° 19' 22"O	clay loam	ACS-QUR	P+D	H year 3	nil	2
28-M	45° 2' 38"N	74° 22' 16"O	sand	QUR	P+D	PM/H years 1,2,3,5	nil	6
29-C	45° 6' 43"N	74° 17' 44"O	stony loam	QUM-QUR	P+D	WM/H years 1,2,3,5	nil	5
29-H	45° 5' 40"N	74° 16' 46"O	stony loam	QUM-QUR	P+D	WM/H years 1,2,3,5	nil	5
29-M	45° 2' 39"N	74° 22' 19"O	sand	QUM-QUR	P+D	WM/H years 1,2,3,5	nil	5
29-S	45° 7' 4"N	74° 22' 18"O	clay	QUM-QUR	P+D	WM/H years 1,2,3,5	nil	5

¹ACS=*Acer saccharum*, JUN=*Juglans nigra*, QUM=*Quercus macrocarpa*, QUR=*Quercus rubra*

²CM=cardboard mulch; D=disking; H=herbicide glyphosate; Hs=herbicide simazine; NP=no soil preparation; P=plowing; PM=plastic mulch; S=strip; WM=wood mulch;

³Deer away™ application

for each plantation combines plantation age and the first letter of the name of the landowner (e.g., plantation 29-C, 29 years of growth on the property of Mr. Caza).

Soil texture varies from sandy to clay, with many loams that are sometimes stony (Table 1). Mechanical soil preparation by plowing and disking was done at 12 sites. This soil preparation was done either on the entire plot or in strips 1.5 to 1.8 m in width (Table 1). At these plantations, post-planting weed control treatments were done using glyphosate herbicide (Roundup™, Monsanto Technology LLC, St. Louis, MO, USA), or black plastic mulch in strips 120-cm wide or with wood chip mulch over a 1 m² area and 5 cm in thickness (Table 1).

Two plantations (26-M, 26-I) did not receive mechanical soil preparation but only post-planting weed control treatment with glyphosate (Table 1). The herbicide treatment in this case was applied over the entire plot in the first year, and in a radius of 60 cm around the seedlings in the second year. For these two plantations, a 0.81 m² (0.9 m X 0.9 m) cardboard-type mulch (Cellufib®, Cascades Etc Inc., Cabano, PQ, Canada) was installed in the third year at the base of each seedling and glyphosate was applied at the margins with a wick applicator (Table 1). The wick application was repeated in the fourth year. One other plantation had a third of its plots that did not receive soil mechanical preparation (27-Lb), but where a post-planting weed control treatment with glyphosate or a black plastic mulch was applied in strips 120-cm width (Table 1). In this case, two herbicide applications were made in the first year and one per year during the following four years.

Deer density having gradually increased in the region, the more recent plantations (16-La, 17-V) received deer browsing protection treatments using a deer repellent (Deer Away® Miller Chemical and Fertilizer, Hanover, PA, USA) (Table 1). Shaping and pruning procedures were done twice at three plantations, three times at two planta-

tions, four times at two plantations, five times at six plantations, and six times at one plantation (Table 1).

Density and thinning

For each species, the area occupied, initial and residual densities, and number of sampled trees in each plantation are presented in Table 2. Several plantations occupy a relatively small area because they were originally planned for research objectives for which it was preferable to have more sites in order to increase edaphic variation. This is the case for 26-M and 26-I, as well as for 29-C, 29-H, 29-M and 29-S (Table 2). The plantations were generally planted at 2000 to 2500 stems/ha, according to the guidelines for the region at that time (Table 2). However, some experimental plantations were planted at a lower density. This is the case for plantations containing black walnut (16-La, 17-V and 18-P). For this species, European publications suggested wider spacing (Becquey 1997; Balleux and van Lerberghe 2001). A thinning cut was done in nine plantations (between 18 to 22 years old), and one plantation had two thinning cuts (28-M) (at 12 years and at 21 years) (Table 2). The stems cut in the thinning operations were left on site or used as firewood. The residual density at the time the data were collected (2016), a result of both mortality and thinning, was on average 25% of the initial density, with a minimum of 14% and a maximum of 58% (Table 2). The residual trees had a mean density of 642 stems per hectare, ranging from 350 to 1480 stems/ha (Table 2).

Tree sampling and measurement

The number of trees measured per species at each plantation is shown in Table 2. Depending on the size of the plantations, from 10% to 100% of the trees were selected to be measured. In the case of plantations with large areas of a single species, 15 consecutive trees were measured in sections of three different rows. The rows chosen for sam-

Table 2. Area occupied, initial and residual densities, thinning frequency and number of sampled trees for each species at each plantation

Species	Age-Site	Area / sp (m ²)	Initial Tree/ha	Thinning frequency	Residual Tree/ha	Sampling (n)
ACS	21-D	3510	2500	1	1450	30
ACS	26-I	300	2500	1	668	15
ACS	26-M	300	2500	1	475	11
ACS	27-R	2500	2000	0	1480	45
JUN	16-La	1855	555	0	455	42
JUN	17-V*	3220	410	0	377	53
JUN	18-P	3240	833	0	708	92
JUN	19-D	1000	2500	1	1071	30
JUN	26-I	300	2500	1	468	14
JUN	26-M	300	2500	1	400	9
QUM	26-I	300	2500	1	668	14
QUM	26-M	300	2500	1	425	7
QUM	27-Lb	6480	2222	1	706	60
QUM	29-C	480	2500	1	480	18
QUM	29-H	480	2500	1	812	26
QUM	29-M	480	2500	1	350	13
QUM	29-S	480	2500	1	550	19
QUR	18-P	3240	833	0	733	95
QUR	26-I	300	2500	1	700	15
QUR	26-M	300	2500	1	500	15
QUR	27-Lt	6000	2000	1	756	45
QUR	27-R	5000	2000	0	860	44
QUR	28-M	1765	2500	2	425	49
QUR	29-C	480	2500	1	416	17
QUR	29-H	480	2500	1	500	19
QUR	29-M	480	2500	1	458	14
QUR	29-S	480	2500	1	450	18

* Walnut rows intercropped with poplar rows (6 m × 3 m)

Table 3. Defects recorded on each of the four faces of a log

Default	Description
Lower bole injury	Injury on the but log
Bump	Protuberance on the bole
Large branch	Branches > 5 cm diameter
Epicormic branch	Twigs > 1 cm diameter or two and more twigs in a radius of 15 cm
Canker	Lesion on the bole of a tree caused by a fungus growth
Check	Sudden axis deviation
Sweep	Gradual axis deviation
Frost crack	Spiralized, deep or superficial cracks
Fork	Main stem division
Knots	Trace left by an old branch
Sapsucker peck	Small holes made by the yellow-bellied sapsucker
Conks	Fungal presence

pling were located in different areas of the plantation and excluded trees on plantation edges. No sampled trees were selected based on apparent tree quality. The initial and current densities of the trees were determined by measuring available data, confirmed by measuring the space between planting rows and the spacing on the rows. A total of 829 trees were measured, including 331 red oaks in

Table 4. Diameter at breast height (DBH; cm), height (m) and height/DBH ratio (and standard deviation SD) for each species at each age-site

Species	Age-Site	DBH	SD	Height	SD	H/D	SD
ACS	21-D	11.2	3.7	10.3	2.8	0.95	0.20
ACS	26-I	14.5	2.8	12.5	2.0	0.87	0.14
ACS	26-M	16.1	5.5	12.0	3.3	0.77	0.11
ACS	27-R	8.6	3.1	8.2	2.5	0.98	0.15
JUN	16-L	14.9	3.7	9.2	2.1	0.62	0.06
JUN	17-V*	11.6	3.4	7.9	2.0	0.70	0.09
JUN	18-P	16.1	4.5	10.5	2.3	0.67	0.09
JUN	19-D	13.6	4.3	9.4	2.4	0.71	0.12
JUN	26-I	18.5	3.3	11.2	1.2	0.61	0.07
JUN	26-M	15.2	5.4	11.8	3.9	0.79	0.11
QUM	26-I	14.0	2.2	9.0	1.4	0.65	0.08
QUM	26-M	17.8	3.4	10.6	1.1	0.60	0.07
QUM	27-Lb	9.9	2.4	6.8	1.3	0.69	0.05
QUM	29-C	18.4	4.4	11.2	2.2	0.62	0.06
QUM	29-H	14.9	4.4	9.8	2.4	0.67	0.09
QUM	29-M	15.1	2.9	10.7	1.9	0.71	0.09
QUM	29-S	17.8	5.0	11.1	2.1	0.64	0.10
QUR	18-P	14.1	3.8	10.2	2.2	0.74	0.09
QUR	26-I	23.3	4.0	14.9	1.6	0.66	0.11
QUR	26-M	22.0	5.2	14.8	3.3	0.68	0.06
QUR	27-Lt	15.1	5.2	11.8	3.7	0.80	0.17
QUR	27-R	18.8	4.8	14.3	2.9	0.79	0.18
QUR	28-M	25.9	4.9	18.2	3.3	0.71	0.07
QUR	29-C	24.8	8.0	15.3	3.1	0.66	0.17
QUR	29-H	26.6	6.1	17.4	3.7	0.67	0.10
QUR	29-M	27.8	5.9	18.7	3.1	0.68	0.07
QUR	29-S	25.9	5.2	16.4	2.2	0.66	0.18

* Walnut rows intercropped with poplar rows (6 m × 3 m)

10 plantations, 240 black walnuts in six plantations, 157 bur oaks in seven plantations, and 101 sugar maples in four plantations (Table 2).

Diameter at breast height (DBH; 1.3 m above ground) outside the bark was measured and the mean DBH per species per plantation is presented (Table 4). Stem quality evolution is positively related to diameter growth (Power and Havreljuk 2016). The mean diameter of trees with a DBH above the median (50%) was also calculated and termed « DBH (+50%) ». These larger trees would be part of the trees retained at the next thinning. The mean annual diameter increment (ADI) and the mean ADI (+50%) were also calculated. The height of trees was measured for a sub-sample of trees selected to cover the range of diameters of each species in each plantation. Thus, depending on the species, 38% to 62% of trees were measured for height. Height measurements were made with a hypsometer (Vertex III, Haglöf Sweden AB, Långsele, Sweden). Regressions for height based on DBH for each species were used to determine a height value for the trees that were measured only for DBH (Jump statistical software, JMP v10.0.0; SAS Institute, Cary, NC, USA).

The defects of the four faces of each stem were determined using the document produced by the Quebec Min-

istry of Forests, Wildlife and Parks (MFFP 2014) (Table 3). Two stem quality evaluators were trained for two days by two specialists to insure that the stem quality evaluation method was well understood and accurately applied. Stems were evaluated for their potential to provide two log sections of 2.6 m (8'6") with a maximum of faces without defects. In cases where obtaining only a single log section was possible, we determined the length of the first log that would maximize the number of faces clear of defects.

All defects were evaluated and the most important defect was recorded for each log. The presence of branches of 5-cm diameter or less on stems with diameters smaller than 12-cm was not considered a defect because the next pruning could ensure that quality is maintained. These branches were rarely present on the first log because pruning had been previously done in all plantations.

Results and discussion

Soil preparation and post-planting weed control treatments have resulted in a generally high survival rate, and plantations with the highest initial densities (> 2000 t/ha) have received a thinning treatment (Table 2). One of these plantations received only one post-planting herbicide treatment in the third year (plantation 27-R, Table 1) and the survival of red oak was the lowest at 43% (residual tree ha^{-1} / initial tree ha^{-1} , Table 2), reducing the need for the first thinning in this plantation (Tables 1 and 2). In this

same plantation, sugar maple and red oak DBH and height values were among the lowest compared to other plantations of similar age (26-29 years old) (Table 4).

The mean variability in diameter values for each species at each plantation varied from 22% to 30%. A significant number of trees with larger diameters is therefore present. Variability is less for height (18% to 25%), and even more so for the H/D ratio (11% to 17%) (Table 4).

Growth results

Sugar maple

Mean annual diameter increment (ADI) for sugar maple varies from 0.53 to 0.62 cm yr^{-1} in three of four study plantations (Fig. 1). The lowest ADI values were obtained in plantation 27-R (0.32 cm yr^{-1}), for which we have already mentioned a minimum herbaceous vegetation control effort (Fig. 1; Table 4). Growth data from nine experimental plantations (19 to 31 years old) reported by McKenney *et al.* (2008) showed an average ADI rate of 0.35 cm yr^{-1} , with a maximum value of 0.49 cm yr^{-1} . Lamson and Smith (1978) measured a mean ADI of 0.47 cm yr^{-1} for 14-year-old sugar maples originating from natural seedlings thinned at nine years. The elite sugar maple trees of our study have an ADI + 50% ranging from 0.64 to 0.76 cm yr^{-1} in three of our four plantations, and of 0.41 cm yr^{-1} in plantation 27-R. With more than 475 trees ha^{-1} (Table 2), the selection of superior trees can be considered in all our

Fig. 1. Bar graphs of annual diameter increment (ADI, cm) and standard deviation for each species at each plantation (age-site). *The underlined values above the bar graphs are the mean value of the ADI (cm) of the 50% of trees that have the largest diameter in each plantation.

plantations, which could lead to a 23% mean improvement of the ADI (Table 4).

Black walnut

The average ADI from black walnut ranged between 0.59 to 0.93 cm yr⁻¹ (Fig. 1), depending on the plantation. The diameter values obtained for black walnut (Table 4, Fig. 1) are comparable to the best results for the species among those obtained in Canadian hardwood plantations in studies by Pedlar *et al.* (2006) (26 years, 16.4 cm DBH, 0.62 cm yr⁻¹ ADI) and by Pedlar *et al.* (2007) (20 & 30 years, 13.6 cm & 20.2 cm DBH, 0.68 cm & 0.67 cm ADI). The superior results of these studies were obtained in mixed plantations, on well-drained loamy or sandy loam soils considered optimal in Ontario (Canada). Our results in Québec were obtained on well-drained stony loam or sandy loam soils (Table 1). Our ADI values are, in general, higher than the ADI of 0.60 cm yr⁻¹ considered “typical” in Indiana (Woeste 2002). Bohanek and Groninger (2003) obtained a mean ADI rate of 0.80 cm yr⁻¹ (DBH = 28.2 cm after 35 years) for black walnut in Illinois in an intensive silvicultural trial with a density of 158 trees ha⁻¹. The black walnut plantations in our study have current densities ranging from 377 to 1071 trees ha⁻¹, making future thinning possible (Table 2). Our elite black walnuts, (ADI + 50%), have ADI rates ranging from 0.73 to 1.11 cm yr⁻¹, with five of our six plantations yielding ADI rates above 0.80 cm yr⁻¹ (Fig. 1). These values correspond to an increase of 21% in mean ADI.

Bur oak

Three plantations have the highest ADI values for bur oak, ranging from 0.61 to 0.69 cm yr⁻¹ (Fig. 1). A second group of three plantations produced intermediate ADI values (0.52 to 0.54 cm yr⁻¹) (Fig. 1). The ADI and tree diameter were the lowest in plantation 27-Lb, with an ADI of 0.43 cm yr⁻¹ (Fig. 1, Table 4). The soil in plantation 27-Lb is relatively thin with bedrock at 80 cm depth, and with a soil rockiness of 30–40% (Cogliastro *et al.* 2003). These characteristics limit the soil volume that can be prospected by roots. The plantation also drains and dries up more rapidly than others because of its higher topographic position.

ADI results of 0.30 cm yr⁻¹ and 0.39 cm yr⁻¹ were produced by 25-year-old trees on two plots of the same Ontario plantation site (McKenney *et al.* 2008). The initial densities of these two plots were high, with respectively 3630 and 2238 trees/ha. Johnson (1990) reported a bur oak ADI ranging from 0.25 to 0.64 cm yr⁻¹ in Iowa and a mean ADI of 0.65 cm yr⁻¹ in Kansas. The most productive bur oaks of our study (ADI + 50%) attain or surpass these higher values (0.59 to 0.77 cm yr⁻¹; Fig. 1), with the exception of bur oaks in plantation 27-Lb (Fig. 1). Our bur oak ADI + 50% values are on average 17% higher than the mean ADI. Tree densities in our plantations will allow a selection of better stems by thinning. Bur oak growth is about half as rapid as that of red oak (Johnson *et al.* 2009; Truax *et al.* 2015).

Red oak

The mean ADI of red oak was higher than 0.80 cm yr⁻¹ in seven of the 10 plantations studied (Fig. 1). The lower ADI values in the remaining three plantations (27-Lt; 27-R; 18-P) ranged from 0.56 to 0.78 cm yr⁻¹. The red oak of plantation 18-P were planted at a spacing of 2 m x 6 m. The 2 m spacing on the row and the absence of a thinning treatment (Table 2) were probably growth limiting. We have already mentioned that the single herbicide application in plantation 27-R could explain the slower growth of sugar maple. This would seem to be the case as well for red oak. Plantation 27-Lt could have some of the lowest growth results because the thinning operation occurred late. The three plantations, 27-Lt, 27-R and 18-P, are also those that have the highest H/D ratios for red oak, which likely reflects the effect of a high planting density (Bartoli and Golf 1994).

From the analysis of four experimental plantations of 35 and 36 years of age, McKenney *et al.* (2008) obtained a mean ADI of 0.47 cm yr⁻¹, producing red oak with a mean DBH of 16 cm. In red oak plantations of south western France, mean ADI values of 0.9 cm yr⁻¹ (± 0.16) were measured at 20–30 years of growth (Timbal *et al.* 1994). Ward (2002) measured ADI from 0.50 to 0.65 cm yr⁻¹ for forest grown red oak ranging from 74 to 94 years that had received a crown release of 50% or higher. Johnson (2009) reported ADI values from 0.72 to 1.02 cm yr⁻¹ in red oak following thinning operations at several average natural sites. The elite red oak of our study have, on average, an ADI + 50% that is 19% higher than the mean ADI, with values ranging between 1.0 and 1.11 cm yr⁻¹ at seven of 11 plantations (Fig. 1).

Stem quality

Sugar maple with a first log without defects occur in the four plantations that were planted for over 84% of trees, with two plantations that have 100% of trees with a first log without defects (Fig. 2A). At three of these plantations, a second log without defects is present for 27%, 29% and 37% of the trees (Fig. 2B).

Four plantations with black walnut had more than 74 % of the trees with a first log without defects, with two plantations with 93% and one plantation with 85% (Fig. 2C). The other two plantations had 56% and 67% of black walnut with a first log without defects (Fig. 2C). Five plantations had from 10% to 21% of black walnut that have a second log without defects on four faces, and the last plantation (16-La) had no second log of interest (Fig. 2D).

First logs for bur oak were 100% without defects at five of our seven plantations (Fig. 2E). The two other plantations had 77% and 86% of trees with perfect first logs (Fig. 2E). Two plantations had 44% and 58% of their second logs without defects, two other plantations had 29% and 19% perfect second logs, one plantation had only 7%, and two plantations had no perfect second log (Fig. 2F). The addition of bur oak second logs with three perfect faces provides a significant increase in bur oak value in these plantations (Fig. 2F).

Fig. 2. Percentage of flawless faces for the first and the second bole length for each species at each plantation age

The plantations of red oak have more than 78% of trees with first logs without defects, with nine plantations out of 10 with more than 88% (Fig. 2G). The amount of red oak second logs without defects are from 30% to 56% of trees for five plantations, and from 7% to 24% for the five other plantations (Fig. 2H). As for bur oak, the addition of red oak second logs with three perfect faces provides a significant increase in red oak value in these plantations (Fig. 2G).

Main defects

There is a small proportion of trees that have defects on their first log but far more have them on their second log (Fig. 2). Among the trees with stem defects, the presence of large branches (> 5 cm diameter) was the most frequent defect encountered in all species (Table 5). Less frequently seen on first logs, and notably absent on bur oak first logs, large branches are the most frequent cause of quality reduction of the second logs of the four study species. The pruning of these branches could have been done earlier but several factors usually justify the delay. Most often these branches cannot all be removed at the same time without weakening the tree, and good judgement must be exercised in choosing which ones to prune. This work also requires more effort and precision when using a pole saw. Subsidies for pruning, when they exist, are limited and address only the initial pruning, mostly for the first log. Large branches on the second log can also appear early on and their removal creates a risk for the sanitary status of the tree. A frequent survey of the trees can help avoid this problem but it can be very time-consuming for the silviculturist. The presence of checks and curves are also frequent defects on the first log of black walnut (Table 5). Checks were also observed on the second logs of sugar maple (Table 5). Cracks, deep or superficial, are also among the defects

recorded for three of the four species examined, with none seen on bur oak (Table 5). Less frequent defects of the first logs consisted of knots (sugar maple) and epicormic branches (red oak) (Table 5). These epicormic branches were, however, most often the cause of the reduction in quality of the second logs for all the studied species (Table 5). The main defect of the first log of bur oaks was the presence of pecking holes by the yellow-bellied sapsucker (*Sphyrapicus varius* L.), but it was seen only in plantations M-26 and M-29 (Fig. 2E, Table 5).

European recommendations for final tree densities in intensive silviculture hardwood plantations mention an objective of 50 to 70 stems/ha for black walnut (Becquey 1997) and from 80 to 200 stems/ha for red oak (Bartoli and Golf 1994; Kenk and Borsy 1994; Thill 1994). These densities are designed to rapidly produce high quality, large first logs, and require several thinning operations. If our current results remain stable over time for our study plantations, the selection of best future trees could allow us to obtain a very high majority of first logs without defects for the four species. However, thinning operations will not guarantee the production of a second perfect log in all plantations. Using the final maximum plantation densities mentioned above, we can expect producing a majority of second perfect logs in the case of two out of four plantations for sugar maple, four out of six plantations for black walnut, three out of seven plantations for bur oak, and of five out of 10 plantations for red oak.

Conclusions

The highest mean annual diameter increments were produced by red oak (0.83 cm yr⁻¹) and black walnut (0.75 cm yr⁻¹). Growth was slower for bur oak (0.55 cm yr⁻¹) and sugar maple (0.51 cm yr⁻¹). These mean annual diameter increments are comparable to, or exceed, the best rates found in the literature. Our elite trees (DBH + 50%) have diameters that are 17% to 23% above the average. In natural hardwood forests, most trees retain their initial quality over time (Power and Havreljuk 2016). By continuing thinning operations, the maximum growth rate of our elite trees could be maintained. With those trees, stems 45 cm DBH could be obtained near to 47 years for red oak, near to 51 years for black walnut, and near to 72 years for bur oak and 77 years for sugar maple. These estimates are based on a smaller number of plantations in the case of sugar maple.

Some of the plantation plots we studied have small areas and this may reduce the potential to generalize the results we obtained. However, the frequent silvicultural interventions required for hardwood plantations in order to produce quality timber, tend to restrict the size of new planted areas established annually, generally from 0.5 ha to 5 ha on private land (Thill 1994; Timbal et al. 1994). Von Althen (1990) noted that these conditions make hardwood planting especially suitable for the small landowner and hobby farmer who may have the time, interest, pride and money to make the plantings a success. In addition, new agroforestry systems are currently being proposed to mitigate the effects of forest fragmentation, the loss of biodiversity and the impacts of intensive agriculture (Jose 2009). These objectives aim at providing ecosystem services for the benefit of society. In addition to the positive environmental effects of these new plantation systems, their profitability

Table 5. Proportion of each of the main defects (>10%) encountered on the 1st and 2nd 2.6 m log sections among boles showing defects

1 st Log Section		2 nd Log Section	
ACS		ACS	
Large branches	42%	Large branches	54%
Deep Straight Cracks	17%	Epicormic branches	23%
Knots	17%	Checks	15%
JUN		JUN	
Checks	27%	Large branches	72%
Large branches	19%	Epicormic branches	11%
Curves	11%		
Superficial straight cracks	11%		
QUM		QUM	
Sapsucker pecks	100%	Large branches	65%
		Epicormic branches	33%
QUR		QUR	
Large branches	39%	Large branches	60%
Superficial straight cracks	16%	Epicormic branches	28%
Epicormic branches	13%		

ACS=Acer saccharum; JUN= Juglans nigra; QUM=Quercus macrocarpa;
QUR=Quercus rubra

has been established in some cases, as with walnut timber (Graves *et al.* 2007; Wolz and Delucia 2019). We hope that the results presented here incite various levels of government to support forest and agricultural landowners in their hardwood plantation endeavours.

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References

- Alam, M., A. Olivier, A. Paquette, J. Dupras, J.-P. Révère and C. Messier. 2014. A general framework for the quantification and evaluation of ecosystem services of tree-based intercropping systems. *Agrofor. Sys.* 88(4): 679–691. doi:10.1007/s10457-014-9681-x.
- Allen, J.A., B.D. Keeland, J.A. Stanturf, A.F. Clewell and H. Kennedy Jr. 2001. A guide to bottomland hardwood restoration. Information and Technology Report, USGS/BRD/ITR-2000-0011, Gen. Tech. Rep. SRS-40, USDA Forest Service.
- Balleux, P. and P. van Lerberghe. 2001. Le boisement des terres agricoles. Institut du développement forestier, Paris. 128 p.
- Bariteau, L. 1988. La carte géomorphologique au 1:20 000 de modèles polygéniques: un exemple des basses terres du Saint-Laurent. Mémoire de maîtrise, Université de Montréal, Montréal.
- Bartoli, M. and N.L. Goff. 1994. La conduite des peuplements en France. In: Le chêne rouge d'Amérique. J. Timbal, A. Kremer, N.L. Goff, and G. Nepveu (eds). Institut national de la recherche agronomique, Paris. pp. 237–246.
- Becquey, J. 1997. Les noyers à bois. 3rd édition, Les Guides du Sylviculteur, Institut pour le développement forestier, Paris. p. 60–61.
- Bergeron, M., S. Lacombe, R.L. Bradley, J. Whalen, A. Cogliastro, M.-F. Jutras and P. Arp. 2011. Reduced soil nutrient leaching following the establishment of tree-based intercropping systems in eastern Canada. *Agrofor. Sys.* 83: 321–330. doi:10.1007/s10457-011-9402-7.
- Bohanek, J.R. and J.W. Groninger. 2003. Impacts of intensive management on black walnut (*Juglans nigra* L.) growth and bole quality at mid-rotation. *For. Sci.* 49: 522–529.
- Cogliastro, A., D. Gagnon and A. Bouchard. 1997a. Experimental determination of soil characteristics optimal for the growth of ten hardwoods planted on abandoned farmland. *For. Ecol. Manag.* 96: 49–63.
- Cogliastro, A., D. Gagnon and A. Bouchard. 1997b. Is site preparation necessary for bur oak receiving post-planting weed control? *Ann. For. Sci.* 54: 107–116.
- Cogliastro, A., D. Gagnon, D. Coderre and P. Bhereur. 1990. Responses of seven hardwood tree species to herbicide, rototilling, and legume cover at two southern Quebec plantation sites. *Can. J. For. Res.* 20(8): 1172–1182.
- Cogliastro, A., D. Gagnon, S. Daigle and A. Bouchard. 2003. Improving hardwood afforestation success: An analysis of the effects of soil properties in southwestern Quebec. *For. Ecol. Manag.* 177: 347–359.
- Davies, R.J. 1988. Sheet mulching as an aid to broadleaves tree establishment I. The effectiveness of various synthetic sheets compared. *Forestry* 61: 89–105.
- Farlee, L.D. 2018. Resources and assistance available for planting hardwood seedlings. Available from <https://www.extension.purdue.edu/extmedia/FNR/FNR-226-w.pdf> [cited 2 may 2019].
- Gardiner, E.S., D.R. Russell, M. Oliver and L.C. Dorris. (2002). Bottomland hardwood afforestation: state of the art. In: Proceedings of a Conference on Sustainability of Wetlands and Water Resources, May 23–25, Oxford, Mississippi, Marjorie M. Holland, Melvin L. Warren, John A. Stanturf (eds). p. 75–86.
- Genet, A., D. Auty, A. Achim, M.D.P. Bernier and A. Cogliastro. 2013. Consequences of faster growth for wood density in northern red oak (*Quercus rubra* Liebl.). *Forestry* 86: 99–100. doi:10.1093/forestry/cps057.
- Globensky, Y. 1987. Géologie des Basses-Terres du Saint-Laurent, Rapport MM 85-02, Québec: Ministère de l'énergie et des ressources, Direction générale de l'exploration géologique et minière, 63 p.
- Graves, A.R., P.J. Burgess, J.H.N. Palma, F. Herzog, G. Moreno, M. Bertomeu, C. Dupraz, F. Liagre, K. Keesman, W. van der Werf, A.K. de Nooy and J.P. van den Briel. 2007. Development and application of bio-economic modelling to compare silvoarable, arable, and forestry systems in three European countries. *Ecol. Eng.* 29: 434–449.
- Hubert, M. and Courraud, R. 1998. Élagage et taille de formation des arbres forestiers. Institut pour le développement forestier. Paris. 303 p.
- Johnson, P.S. 1990. *Quercus macrocarpa* Michx. In: Silvics of North America: 2. Hardwoods, Agriculture Handbook 654. USDA, Forest Service, Washington, DC. pp. 686–692.
- Johnson, P.S., Shifley, S.R., and Rogers, R. 2009. Ecology and Silviculture of Oaks - 2nd ed. CABI North American Office, Cambridge, MA.
- Jose, S. 2009. Agroforestry for ecosystem services and environmental benefits: an overview. *Agrofor. Sys.* 76: 1–10.
- Kenk, G. and P. Borsy. 1994. Le chêne rouge (*Quercus borealis* Michx.) en Allemagne. In Le chêne rouge d'Amérique. J. Timbal, A. Kremer, N.L. Goff, and G. Nepveu (eds). Institut national de la recherche agronomique, Paris. pp. 265–271.
- Lambert, M.-C., C.-H. Ung and F. Raulier. 2005. Canadian national tree aboveground biomass equations. *Can. J. Forest. Res.* 35: 1996–2018.
- Lamson, N. I. and H.C. Smith. (1978). Response to crop-tree release: Sugar maple, red oak, black cherry, and yellow-poplar saplings in a 9-year-old stand. Res. Pap. NE-394. Broomall, PA: USDA, Forest Service, Northeastern Exp. Station.
- McKenney, D., D. Allen, S. Fraleigh, J. Pedlar and K. Campbell. 2008. Growth of southern Ontario hardwood research plantations. *Can. For. Serv. Great Lakes For. Cent. Inf. Rep.* 2562-0738; GLC-X-9E.
- Meilleur, A., A. Bouchard and Y. Bergeron. 1994. The relation between geomorphology and forest community types of the Haut-St-Laurent, Québec. *Vegetatio* 111: 173–192.
- MELCC. 2010. Climate summary 1981–2010. Available from <http://www.environnement.gouv.qc.ca/climat/normales/somme-maire.asp> [cited February 2019].
- MFFP. 2014. Classification des tiges d'essences feuillues [Hardwood stem classification, in French]. Ministère des Forêts, de la Faune et des Parcs Secteur des forêts, Direction des inventaires forestiers. Québec. Available from <https://mffp.gouv.qc.ca/publications/forets/connaissances/classif-tiges-essence-feuillues-6.pdf> [cited april 2019].
- Ostfeld, R.S., R.H. Manson and C.D. Canham. 1997. Effects of rodents on survival of tree seeds and seedlings invading old fields. *Ecology* 78: 1531–1542.

- Pedlar, J.H., D.W. McKenney and S. Fraleigh. 2006.** Planting black walnut in Southern Ontario: midrotation assessment of growth, yield, and silvicultural treatments. *Can. J. For. Res.* 36: 495–504.
- Pedlar, J.H., S. Fraleigh and D.W. McKenney. 2007.** Revisiting the work of Fred von Althen – an update on the growth and yield of a mixed hardwood plantation in Southern Ontario. *For. Chron.* 83: 175–179.
- Power, H. and F. Havreljuk. 2016.** Predicting hardwood quality and its evolution over time in Quebec's forests. *Forestry* 91: 259–270. doi:10.1093/forestry/cpw059%.
- Saura, S., L. Bastin, L. Battistella, A. Mandrici and G. Dubois. 2017.** Protected areas in the world's ecoregions: How well connected are they? *Ecol. Indi.* 76: 144–158.
- Stanturf, J.A., S.H. Schoenholtz, C.J. Schweitzer, C.J. and J.P. Shepard. 2001.** Achieving restoration success: Myths in bottom-land hardwood forests. *Restor. Ecol.* 9: 189–200.
- Thill, A. 1994.** La sylviculture du chêne rouge d'Amérique en Belgique. *In: Le chêne rouge d'Amérique.* J. Timbal, A. Kremer, N.L. Goff, and G. Nepveu (eds). Institut national de la recherche agro-nomique, Paris. pp. 254–264.
- Timbal, J., B. Pilard-Landeau, B. Lemoine and J. Gelpe. 1994.** Le chêne rouge d'Amérique dans le Sud-Ouest de la France. *In: Le chêne rouge d'Amérique.* Institut National de la Recherche Agro-nomique, France, Paris. pp. 151–176.
- Truax, B. and D. Gagnon. 1993.** Effects of straw and black plastic mulching on the initial growth and nutrition of butternut, white ash and bur oak. *For. Ecol. Manage.* 57: 17–27.
- Truax, B., D. Gagnon, F. Lambert and J. Fortier. 2015.** Multiple-use zoning model for private forest owners in agricultural landscapes: A case study. *Forests* 6: 3614–3664.
- von Althen, F.W. 1990.** Hardwood planting on abandoned farmland in southern Ontario: Revised guide. Minister of Supply and Services Canada. Catalogue No. Fo 42-150/1990E.
- Ward, J.S. 2002.** Crop tree release increases growth of mature red oak sawtimber. *North. J. Appl. For.* 19: 149–154.
- West, P.W. 2006.** Growing plantation forests. Springer-Verlag Berlin Heidelberg.
- Woeste, K.E. 2002.** Heartwood production in a 35-year-old black walnut progeny test. *Can. J. For. Res.* 32: 177–181.
- Wolz, K.J. and E.H. Delucia. 2019.** Black walnut alley cropping is economically competitive with rowcrops in the Midwest USA. *Ecol. Appl.* 29: e01829.
- Zhang, Y., C. Peng, W. Li, L. Tian, Q. Zhu, H. Chen and Z. Li. (2016).** Multiple afforestation programs accelerate the greenness in the 'Three North' region of China from 1982 to 2013. *Ecol. Indic.* 61: 404–412.