NRC Research Press

ARTICLE

Bur oak (*Quercus macrocarpa*) biomass production on a former coal mine site: positive effects of coppicing on rapid recovery of growth and yield

A. Mosseler, J.E. Major, and D. McPhee

Abstract: Ten-year-old bur oak (*Quercus macrocarpa* Michx.) saplings established on the exposed, infertile, treeless barrens of a former coal mine site in New Brunswick, Canada, were harvested to assess the effects of subsequent coppicing on regrowth parameters and biomass production. Two years after harvesting, coppice height growth exceeded that of the original 10-year-old saplings by 20%. Mean stem numbers were 1.2 and 6.7 for 10-year-old and coppiced trees, respectively. Mean dry mass recovered after 2 years with 214, 112, and 207 g for 10-year-old saplings and the 1- and 2-year-old coppices, respectively. Site quality of the broken shale rock overburden was similar across four of the five sites, with the exception that one site had twice the soil nitrogen (N) at 0.123% than the other four site types, which had an average of 0.064% N. This high N site had 2.3-fold the productivity of the mean for the other four sites. Mean coppice stem height showed the strongest predictive relationship to total coppice dry mass when compared with the greatest stem height, greatest or mean stem basal diameter, or coppice stem number. The most dramatic result of this bur oak coppicing experiment was the rapid recovery of height growth, biomass production, and observable stem quality within coppices over the 2-year period following harvesting of the original, 10-year-old saplings.

Key words: biomass production, bur oak, coppicing effect, mine reclamation, soil quality.

Résumé : De jeunes tiges de chêne à gros fruits (*Quercus macrocarpa* Michx.) établies sur des terrains infertiles, exposés et dépourvus d'arbres sur le site d'une ancienne mine de charbon du Nouveau-Brunswick, au Canada, ont été récoltées pour évaluer les effets d'un recépage subséquent sur les paramètres de la repousse et sur la production de biomasse. Deux ans après la récolte, la croissance en hauteur des rejets dépassait de 20 % celle des gaules originales âgées de 10 ans. Le nombre moyen de tiges atteignait 1,2 chez les arbres âgés de 10 ans et 6,7 dans le cas des rejets. La masse anhydre moyenne avait récupéré après deux ans, avec respectivement 214, 112 et 207 g pour les gaules âgées de 10 ans, et les rejets âgés d'un et de deux ans. La qualité de station sur des morts terrains de schiste brisé était similaire pour quatre des cinq stations, excepté une station où la quantité d'azote (N) atteignait le double de celle contenue dans le sol des quatre autres stations, soit 0,123 % comparativement à une moyenne de 0,064 % de N. Cette station riche en N avait une productivité 2–3 fois plus élevée que la moyenne des quatre autres stations. La hauteur moyenne des rejets était le plus étroitement reliée à la masse anhydre totale comparativement à la hauteur maximum de la tige, au diamètre moyen ou maximum à la base de la tige ou au nombre de rejets. Le résultat le plus remarquable de cette expérience de recépage du chêne à gros fruits est la récupération rapide de la croissance en hauteur, de la production de biomasse et de la qualité évidente de la tige des rejets au cours des deux années qui ont suivi la récolte des gaules âgées de 10 ans. [Traduit par la Rédaction]

Mots-clés : production de biomasse, chêne à gros fruits, effet du recépage, restauration minière, qualité du sol.

Introduction

Coppicing is an ancient form of forest management that relies on regeneration from stem sprouting at the root collar following the removal of aboveground biomass (see del Tredici 2001). Under natural conditions, coppice stems result following natural or artificial disturbances such as fire, wildlife browsing, or forest harvesting (Pyttel et al. 2013; Monteiro-Henriques and Fernandes 2018). This method of forest regeneration fell into disuse and disrepute across much of Europe following the 1800s, largely because professional foresters believed coppicing produced poor quality stems for timber production (Vild et al. 2013; Mullerova et al. 2014, 2015; Martin et al. 2015; Vrska et al. 2016). However, coppicing has recently experienced renewed interest for maintaining forest cover and habitat on exposed or dry, infertile sites, particularly in mountainous terrain subject to erosion in the absence of forest cover (Svátek and Matula 2015; Vrska et al. 2016; Stojanović et al. 2017), and because of recent interest in renewable bioenergy (Pyttel et al. 2013). The ability of coppiced plants to better withstand drought or soil infertility than newly planted seedlings is based on the simple premise that the intact root system of a well-established, older plant is more resistant to the adverse effects of drought than the root system of a young, newly planted seedling. This may be especially true on the infertile, exposed, treeless, rocky barrens of the former Salmon Harbour coal mine site in New Brunswick (NB), Canada, where bur oak was planted for the present study.

Although coppicing of upland hardwoods has not been prominent in North American silviculture, it has been used for oak management in the southern Appalachian Mountains where early, rapid height growth gives stump sprouts a competitive advantage over artificially established seedlings (Lockhart and Chambers 2007). Coppice management in some parts of North America may also be experiencing a renaissance as an alternative

Received 18 February 2019. Accepted 13 May 2019.

A. Mosseler, J.E. Major, and D. McPhee. Natural Resources Canada, Canadian Forest Service – Atlantic Forestry Centre, Fredericton, NB E3B 5P7, Canada.
Corresponding author: A. Mosseler (email: Alex.Mosseler@canada.ca).

to clearcutting followed by tree planting (Atwood et al. 2009). In China, coppicing has been an important forest management tool for several native oak species in mountainous terrain (Fang et al. 2011; Xue et al. 2013). With increasing concern about the effects of climate warming and drought on successful forest regeneration and survival of oak forests and associated biodiversity (Gentilesca et al. 2017; Kotlarz et al. 2018; Monteiro-Henriques and Fernandes 2018; Perkins et al. 2018), silvicultural systems based on coppicing may become more important in maintaining oaks, especially at the limits of their range with respect to drought.

In North America, bur oak (*Quercus macrocarpa* Michx.) is predominantly a temperate zone species ranging from southern Saskatchewan to a geographically disjunct population in southeastern NB and across the central and eastern United States (US), reaching as far south as Texas (Johnson 1990). In Canada, bur oak occurs under a wide range of soil fertility and moisture conditions, and at the northernmost limits of its range, it can be found on shallow, droughty soils (Farrar 1995). In NB, bur oak occurs as small, isolated forest remnants, often associated with floodplain forests, an atypical habitat, and thus was probably established by Mi'kmaq and Maliseet First Nations people as they travelled along the major river systems of eastern Canada (McPhee 2001; McPhee and Loo 2009). Currently, bur oak is primarily found in the Grand Lake Basin of southeastern NB (Hinds 1986), which also contains the Salmon Harbour coal mine spoils where bur oak was planted for land-reclamation purposes. This region has the warmest climate in NB, with an annual growing degree-day (temperatures > 5 °C) regime that can exceed 1800. Although NB genotypes were not included in their sample of a range-wide study of isozyme variation, Schnabel and Hamrick (1990) found that genetic diversity levels in bur oak were comparable with levels in other oak species, and similar levels of genetic diversity were confirmed by McPhee (2001) for the disjunct NB population of bur oak.

Soil and site characteristics can influence growth, stem-sprouting ability, and coppice formation in oaks (Gracia and Retana 2004). According to Johnson (1990), bur oak sprouts vigorously following burning or cutting of smaller saplings or trees, but the growth response of coppice production has not been quantified. Atwood et al. (2009) reported significant variation in sprouting ability among several North American oaks, including red oak (*Quercus rubra* L.), chestnut oak (*Quercus prinus* L.), black oak (*Quercus velutina* Lam.), scarlet oak (*Quercus coccinea* Münchh.), and white oak (*Quercus alba* L.) in southern Appalachian forests, but little information is available from the literature on either coppicing response or biomass production in bur oak. However, stem sprout development and biomass production following coppicing were assessed specifically for bioenergy purposes in an oak species native to China (Fang et al. 2011). Currently, coppicing is largely associated with production of woody biomass for bioenergy from short-lived hardwood species such as poplars (*Populus* spp.) and willows (*Salix* spp.), where the aim has been to maximize wood volumes on very short cutting cycles of 1–3 years (Labrecque and Teodorescu 2005; Volk et al. 2006; Mosseler et al. 2014*b*). Coppice structure has an influence on overall productivity. There are often trade-offs between number of stems and mean stem height or basal diameter (Mosseler and Major 2016); however, in taller, longer-lived, and higher value trees such as oaks, coppicing can change the vertical structure of forests, affecting habitat quality for wildlife, including bird species using tree crowns and forest cover (Fuller and Henderson 1992; DeGraaf et al. 1998; Beskardes et al. 2017).

The putative drought tolerance of bur oak (Johnson 1990; Gilman and Watson 1994) suggested that this species might be useful for reclaiming large areas of highly disturbed mine spoils from surface coal mining operations that cover hundreds of square kilometres near Minto, NB, Canada. The shale rock overburden at the former Salmon Harbour coal mine is characterized by the low fertility common to many of the coal mine spoils across the Appalachian region of eastern North America, typified by a lack of organic matter and low nitrogen (N) and phosphorus (P) content (Zipper et al. 2011; Mosseler et al. 2014*a*, 2014*b*). We were interested in how site variability on a dry, infertile shale overburden might affect stem sprouting and coppice regrowth in 1- and 2-year-old coppices following harvesting of 10-year-old saplings of bur oak. We hypothesized that (*i*) coppiced bur oak would reach between 50% and 80% of the growth achieved by 10-year-old saplings within 2 years after harvesting of the saplings, (*ii*) site differences could affect coppice regrowth, and (*iii*) by quantifying variation in coppice response in terms of height and diameter growth, coppice stem number, biomass yield, and their interrelationships, we could provide simple, yet robust, nondestructive aboveground biomass estimation.

Materials and methods

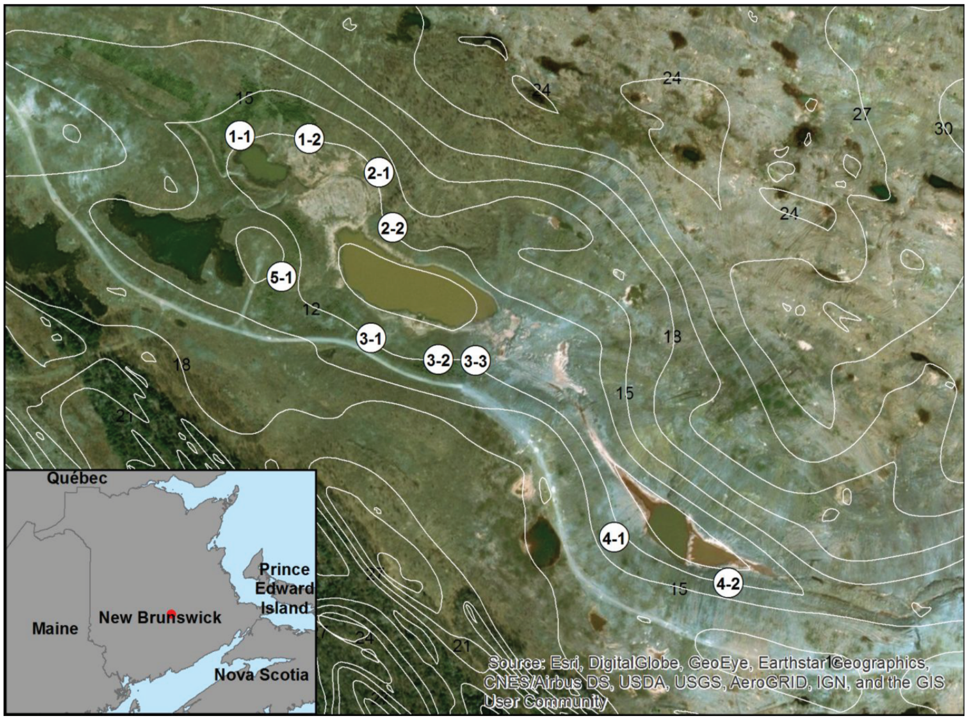
This study was conducted at the Salmon Harbour coal mine spoils, a property operated by NBCoal Ltd., a subsidiary of the local electrical power utility, NBPower (46°07′N, 66°05′W). Seeds for the bur oak planted at Salmon Harbour were collected in 2005 from 21 trees representing seven of the eight remaining bur oak stands in NB (McPhee 2001). Seeds were overwintered at 3 °C and then germinated in March 2006. The germinated acorns were transplanted to containers with a cell volume of 320 cm^3 containing a 2:1:1:2 mixture of peat, loam, aggregate, and perlite, respectively, in May and planted on the mine site in June 2006. Seedlings were planted with their root ball intact at a spacing of approximately 5 m, but planting spots were selected based on ease of planting amidst the rocks that dominated the site rather than a set planting grid. Seedlings were first assessed for survival and growth performance in June 2008 (2 years after establishment), at which time they had attained an average height of 34.4 cm and an average root collar diameter of 4.8 mm and had a very high survival rate of 99.3% (298/300 seedlings alive at age 2 years).

Seedlings were established in 10 groups of 25 seedlings per group (see map in Fig. 1) with each 25-tree group or block within a site type separated by distances ranging from 12 m to 90 m, with an average of 38 m. The 10 blocks were separated into five different site types based on physical proximity, aspect, and similarity of the blocks to test for the effects of site differences on growth and coppice biomass traits. Site 5 contained only one block (or replicate) of 25 bur oak saplings, because it was spatially separated and distinct for its high soil N content from the other four sites assessed in our ANOVA. The five different site types all consisted of similar broken shale rock overburden, the result of landscaping by heavy equipment following cessation of surface coal mining operations in 2005.

After leaf fall in November 2015, in their 10th growing season after establishment, 10 seedlings from each of the 10 groups of 25 trees were randomly selected and labeled. The number of stems was counted, and the dominant stem per sapling was measured for height to the nearest 1.0 cm; basal stem diameter at the root collar was measured to the nearest 1.0 mm, and mass of the leafless aboveground green mass was measured to the nearest 1.0 g following harvesting at the root collar. A single 20 cm stem section removed from the centroid of the dominant stem of each of the 10 harvested saplings in each of the 10 groups of 25 seedlings was weighed to obtain the green mass (g) to determine percent moisture content. This bulked sample of 10 stem sections was dried in an oven for 5 days at 105 °C, at which point, the oven-dried mass of the stems had stabilized and was measured to the nearest 1.0 g. This dry mass measurement was used to calculate the oven-dried biomass of each harvested plant from each of the 10 harvested groups (or blocks in the ANOVA).

After leaf fall in November 2016, the number of coppice stems arising from the root collar of the 10-year-old saplings that had been harvested the previous year (November 2015) was counted

Fig. 1. Map showing the location of 10 groups (blocks) of 25 bur oak saplings organized into five site types (e.g., site 1 consists of groups 1–1 and 1–2, site 2 consists of groups 2–1 and 2–2, etc.) established at the former Salmon Harbour coal mine near Minto, New Brunswick, Canada. The average distance between blocks within site types is 38 m and ranges from 12 m to 90 m. [Colour online.]



on five randomly selected coppiced plants from the 10 harvested at each block of 25 saplings. The green mass of the coppiced stems was weighed to the nearest 1.0 g. The height and stem basal diameter of up to six of the tallest coppice stems were measured. A 20 cm stem section was removed from the centroid of the three largest coppice stems from each of the five harvested coppice plants, and the bulked stem sample was weighed to the nearest 1.0 g to determine percent moisture content. The same process described above was used in the November 2017 harvest of the five remaining 2-year-old coppiced plants from each of the 10 blocks (groups of 25 seedlings).

In November 2016, three soil samples were collected to a depth of 15 cm from each of the five site types for a soil analysis (Table 1). Soil analyses were conducted by the Laboratory for Forest Soils and Environmental Quality at the University of New Brunswick in Fredericton, NB, according to McKeague (1978) as follows: available P, #TP-CSS-MSSA 4.41 (sodium bicarbonate extraction); exchangeable cations, #TP-CSS-MSSA 4.5, FCMM 15 (ammonium acetate extraction); pH, #TP-CSS-MSSA3.13 (pH in 1:1 water); texture, #TP-CSSMSSA 2.12 (hydrometer method); and organic matter, N, carbon (C), and sulfur (S), #TP-LFIM (total C by LECO induction furnace).

Biomass traits (e.g., stem height, stem basal diameter, coppice stem number, and oven-dried mass of aboveground leafless plant biomass) were subjected to analysis of variance (ANOVA). Plant form (10-year-old sapling, 1-year-old coppice, and 2-year-old coppice) and site type were considered fixed effects. Blocks of 25 trees were considered as random effects nested within site type. The following model describes the ANOVA:

$$Y_{ijkl} = \mu + B_{i(j)} + S_j + F_k + SF_{jk} + e_{ijkl}$$

where Y_{ijkl} is the dependent plant trait of block i (25-tree group) of site type j of plant form k (10-year-old saplings and 1- and 2-year-old coppiced plants), and plant l within each block; μ is the overall mean; $B_{i(j)}$ is the effect of block i (i = 1, …, 3) nested within site j (j = 1, …, 5) for plant form k (k = 1, …, 3); and e_{ijkl} (l = 1, …, 5) is the random error component. Differences among traits were considered significant at P = 0.05.

Covariate analysis was used to evaluate the relationships among mean stem height, basal diameter, stem number, and coppice dry mass to test the year of coppice harvest effect. In these analyses, three sources of variation were studied: (*i*) covariate (i.e., stem number), (*ii*) independent effect (i.e., coppice year), and (*iii*) independent effect × covariate. The analyses were done based on the following model:

$$Y_{ij} = B_0 + B_{0i} + B_1X_{ij} + B_{1i}X_{ij} + e_{ij}$$

where Y_{ij} is the dependent trait of plant i of coppice year treatment j; B_0 and B_1 are average regression intercept coefficients; B_{0i} and B_{1i} are the independent slope coefficients; X_{ij} is the independent variable; and e_{ij} is the error term. Results were considered statistically significant at P = 0.05. Tukey's means separation test was used. The data satisfied normality and equality of variance assumptions. The general linear model from SYSTAT (version 12; Systat Software, Inc., Chicago, Illinois) was used for analysis.

Results

Soil properties were reasonably uniform, with the exception of the proportions of sand, silt, and clay, which showed statistically significant, but not large, differences from one site type to another (Table 1). The main distinguishing feature was the soil N content of site 5 (Fig. 1), which was almost twice as great as that found on the other four sites.

The greatest stem height per plant showed significant differences among the three plant forms (10-year-old saplings and 1- and 2-year-old coppices), accounting for 9% of the total variation (Table 2). Stem height of 2-year-old coppices was 20% greater than

Table 1. Soil properties for the five site types at Salmon Harbour coal mine.

Site	Organic matter (%)	Carbon (%)	Nitrogen (%)	Potassium (meq·100 g^{-1})	Calcium (meq·100 g^{-1})	Magnesium (meq·100 g^{-1})	Phosphorus (ppm)	Sulfur (%)	Sodium	C:N ratio	pH	Sand (%)	Silt (%)	Clay (%)
1	1.05±0.13a	0.61±0.08a	0.071±0.010b	0.166±0.020a	5.05±1.06a	0.64±0.12a	3.68±1.10a	0.114±0.023a	0.031±0.008a	9.1±1.7a	6.1±0.8a	57.1±2.3a	28.4±2.3ab	14.4±1.0bc
2	1.21±0.13a	0.70±0.08a	0.060±0.017b	0.141±0.020a	6.62±1.06a	0.65±0.12a	3.85±1.10a	0.074±0.023a	0.010±0.008a	7.9±1.7a	6.9±0.8a	61.4±2.3a	27.3±2.3b	11.3±1.0c
3	1.22±0.13a	0.71±0.08a	0.063±0.010b	0.178±0.020a	5.77±1.06a	0.75±0.12a	4.20±1.10a	0.064±0.023a	0.021±0.008a	11.3±1.7a	5.8±0.8a	46.5±2.3bc	37.3±2.3ab	16.1±1.0b
4	1.16±0.13a	0.68±0.08a	0.063±0.010b	0.210±0.020a	7.27±1.06a	0.87±0.12a	3.11±1.10a	0.100±0.02 a	0.019±0.008a	9.8±1.7a	5.8±0.8a	41.4±2.3c	38.4±2.3a	20.5±1.0a
5	1.14±0.13a	0.66±0.08a	0.123±0.010a	0.200±0.020a	5.96±1.06a	0.68±0.12a	2.98±1.10a	0.088±0.023a	0.025±0.008a	5.4±1.7a	6.2±0.8a	53.5±2.3ab	29.8±2.3ab	16.7±1.0ab

Note: Sites followed by different letters are significantly different using Tukey's mean separation test, $P = 0.05$.

that of the 10-year-old saplings (Fig. 2*a*). Site type was significant and accounted for 14% of the variation. This was largely due to greater stem height on site type 5 (Fig. 1), which was 138 cm vs. the average of 93 cm for the other four site types, or a 50% greater stem height. There was no significant interaction between plant form and site type, illustrated by 2-year-old coppice stem heights being consistently greater than the 10-year-old saplings over all five site types. The greatest stem basal diameter had a similar but also somewhat different response than stem height. Plant form and site type accounted for 35% and 9% of the total variation (Table 2), and stem basal diameters reached only 50% and 72% of the 10-year-old saplings for the 1- and 2-year-old coppices, respectively (Fig. 2*b*). Site type 5 had 46% greater basal diameter than the average of the other four sites types.

Plant form accounted for only 7% of total variation in aboveground dry mass, and overall, the 10-year-old saplings and 2-year-old coppices were virtually equal at 214 and 207 g, respectively (Table 3; Fig. 3*a*). Site type accounted for 11% of the variation because of site type 5, which had 2.3-fold the productivity of the average of the four other sites. Even though the plant form × site type interaction was not significant ($P = 0.186$), the 10-year-old saplings had greater aboveground dry mass than the 2-year-old coppices on site type 5; whereas, on the other four site types, the 2-year-old coppices had aboveground dry mass greater than, or equal to, that of the 10-year-old saplings. Plant form had overwhelmingly the greatest effect on the total variation in stem number, accounting for 56% (Table 3). Stem numbers were 1.2, 7.3, and 6.2 for 10-year-old saplings and 1- and 2-year-old coppices (Fig. 3*b*), respectively. Stem numbers were not significantly different for 1- and 2-year-old coppices. Site type had no significant effect on stem number.

Covariate analysis of coppice dry mass in relation to mean coppice stem height (*x* axis), while testing for a coppice year effect, showed that the coppice year × mean coppice stem height interaction was significant ($P = 0.005$). This resulted in two different slopes for 1- and 2-year-old coppices, with the latter having a steeper slope (Fig. 4*a*). The overall R^2 was high (0.721) and greater than that of the greatest stem height ($R^2 = 0.671$, not shown), showing that mean coppice stem height is a good predictor of aboveground coppice dry mass. Covariate analysis of mean aboveground coppice dry mass in relation to mean coppice stem basal diameter (*x* axis), while testing for a coppice year effect, showed that coppice year × mean coppice basal diameter interaction was significant ($P = 0.043$). This resulted in two statistically different slopes, with 2-year-old coppice having a slightly greater slope than 1-year-old coppice (Fig. 4*b*). The R^2 was high (0.695) and was greater than using the greatest coppice basal diameter ($R^2 = 0.650$, not shown). Stem number was significantly related to mean aboveground coppice dry mass, with separate slopes for 1- and 2-year-old coppices (stem number × coppice year interaction, $P = 0.007$; Fig. 4*c*). Stem number accounted for less variation in describing total aboveground coppice dry mass ($R^2 = 0.453$) than mean coppice stem height or mean stem basal diameter.

Mean coppice stem height in relation to stem number showed no coppice year × stem number interaction ($P = 0.820$). Coppice year was significant ($P < 0.001$), producing two separate lines but equal and slightly positive slopes for describing mean coppice stem height in relation to stem number (Fig. 5*a*). Mean coppice stem basal diameter in relation to stem number showed no coppice year × stem number interaction ($P = 0.695$). Coppice year was significant ($P < 0.001$), resulting in two separate lines, but with equal and slightly positive slopes describing mean stem basal diameter in relation to stem number (Fig. 5*b*).

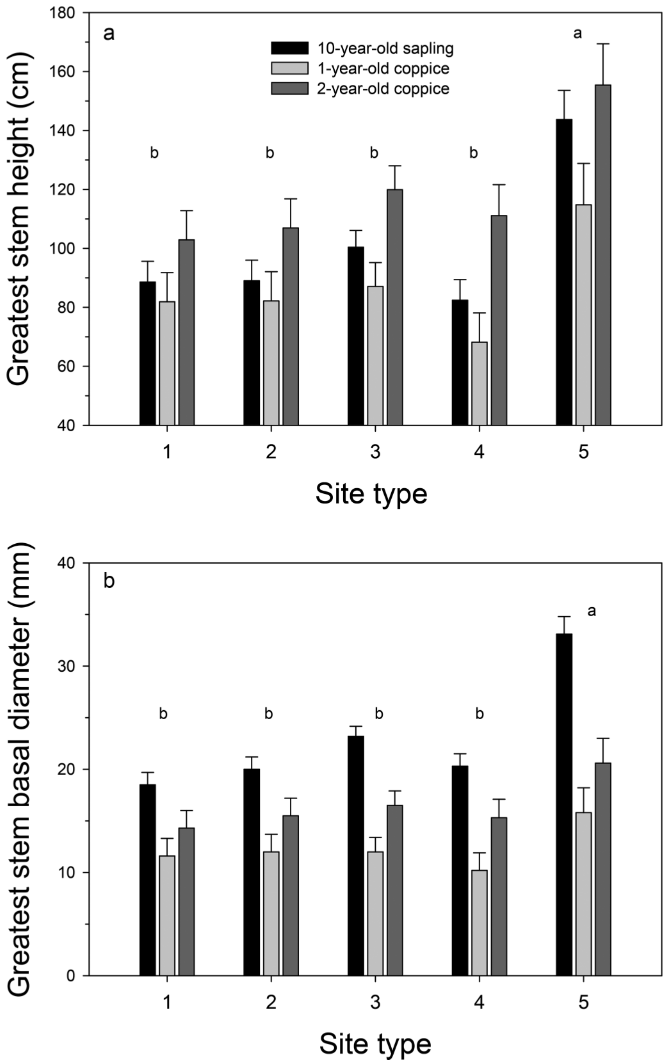
Mean coppice stem height in relation to mean coppice stem basal diameter showed no coppice year × mean stem basal diameter interaction ($P = 0.501$), nor was there a coppice year effect ($P = 0.294$). Thus, there was one positive line for both coppice years,

Table 2. Bur oak maximum stem height and stem basal diameter variance components (Var. comp.) and ANOVAs, including source of variation, degrees of freedom (df), mean square values (MS), *P* values, and coefficient of determination (R^2).

		Greatest stem height (cm)			Greatest stem basal diameter (mm)		
Source of variation	df	MS	Var. comp. (%)	*P* value	MS	Var. comp. (%)	*P* value
Block(site type)	5	3059	6.0	**0.011**	100.2	4.7	**0.004**
Plant form	2	11 553	9.1	**<0.001**	1827.7	34.7	**<0.001**
Site type	4	9107	14.3	**<0.001**	246.6	9.4	**<0.001**
Plant form × site type	8	312	1.0	0.960	45.2	3.4	0.127
Error	179	992	69.7		28.2	47.8	
R^2				0.333			0.544

Note: *P* values < 0.05 are in bold type.

Fig. 2. (*a*) Greatest stem height (cm) and (*b*) greatest stem basal diameter (mm) by site type and plant form.



which describes the mean coppice stem height to mean coppice basal diameter relationship with a high R^2 (0.837) (Fig. 5*c*).

Discussion

The most dramatic result of this bur oak coppicing experiment was the rapid recovery of height growth, biomass production, and observable stem quality in coppices over the 2-year period following harvesting of the original, 10-year-old saplings. Contrary to expectations, coppices were observed to have a straighter, more upright stem form than that of the often misshapen and twisted single-stemmed 10-year-old saplings. If stem numbers and the observable stem quality resulting from coppicing are maintained into the future, the coppiced plant structure could result in a fuller and more spreading tree crown and canopy structure for wildlife and could also improve stem quality for timber and bioenergy production. The coppice stems may have benefited from some interstem competition, as indicated by the mildly positive effect of coppice numbers on height growth up to a maximum of 17 coppice stems (Fig. 5*a*).

This beneficial "coppicing effect" on stem height and, to a lesser extent, on stem basal diameter contrasts with allometric studies of several willow species tested on the same mine site and other sites in which a negative relationship was observed for stem height and stem basal diameter in relation to coppice stem number in five of the seven willow species assessed (Mosseler et al. 2014*a*; Mosseler and Major 2016). It should be noted that coppice stem number was greater, particularly for shrub willows, which have a much larger number and range of coppice stem numbers, particularly in *Salix eriocephala* Michx., which produced up to 76 stems from a single coppice (Mosseler and Major 2016). Contrasted with tree-formed willows such as *Salix amygdaloides* Andersson and *Salix nigra* Marshall, stem numbers were comparable with bur oak, which also produced up to 10 stems per coppice. For *S. nigra*, stem heights were only slightly negatively affected by stem number; whereas stem height in *S. amygdaloides* was negatively affected by coppice stem number. For both of these tree willows, stem basal diameter was negatively affected by coppice stem number.

For predicting total aboveground biomass in bur oak based on nondestructive sampling techniques, either the mean stem height or the mean stem basal diameter of up to six stems per coppice had better predictive value than using only the largest stem per coppice. Based on Mosseler and Major (2016), there was some expectation that coppice stem number would be as good as, or better than, mean stem height or mean stem basal diameter in predicting total aboveground biomass; however, in bur oak, coppice stem number was significant as a predictor of aboveground biomass but not as useful as mean stem height or mean stem basal diameter. Thus, bur oak genotype selection for improved biomass production should include the whole coppice structure: mean stem height, mean stem basal diameter, and coppice stem number. Apparently, species capable of producing large numbers of coppice stems such as *Salix eriocephala* and *Salix interior* Rowlee show a stronger relationship between stem number and aboveground biomass, and this relationship can be useful as a selection criterion for predicting improved biomass productivity (Fatemi et al. 2011; Mosseler and Major 2016).

Relationships between mean stem height and mean stem basal diameter vary among species (Ter-Mikaelian and Korzukhin 1997; Paul et al. 2013; Mosseler and Major 2016) and among sites (Koeper and Richardson 1980; Gargaglione et al. 2008; Mosseler et al. 2014). We found that with bur oak, the mean stem height to mean stem basal diameter ratio was the same regardless of coppice age (1- and 2-year-old); however, others have found that age is also an impor-

Table 3. Bur oak aboveground dry mass and stem number variance components (Var. comp.) and ANOVAs, including source of variation, degrees of freedom (df), mean square values (MS), *P* values, and coefficient of determination (R^2).

		Aboveground dry mass (g)			Stem number		
Source of variation	df	MS	Var. comp. (%)	*P* value	MS	Var. comp. (%)	*P* value
Block (site type)	5	327.1×10^3	6.4	**0.008**	5.2	1.8	0.143
Plant form	2	334.5×10^3	6.6	**<0.001**	694.9	56.2	**<0.001**
Site type	4	550.7×10^3	10.9	**<0.001**	8.5	1.4	0.169
Plant form × site type	8	233.4×10^3	4.6	0.186	8.3	2.7	0.134
Error	179	3612.3×10^3	71.5		5.2	37.9	
R^2				0.336			0.630

Note: *P* values < 0.05 are in bold type.

Fig. 3. (*a*) Total aboveground dry mass and (*b*) stem number by site type and plant form.

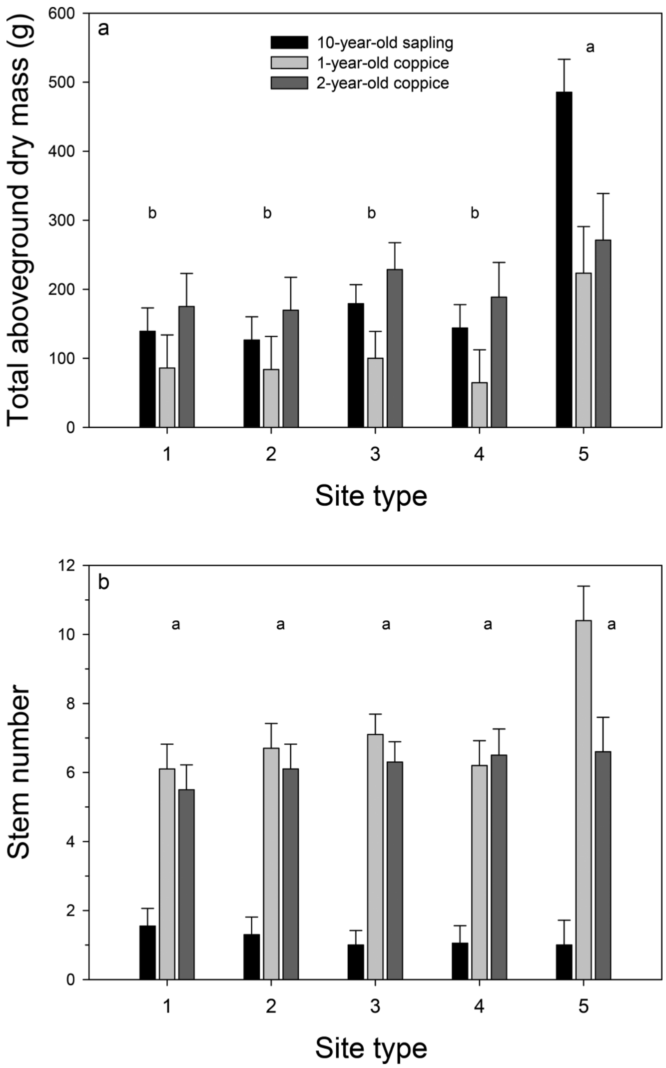
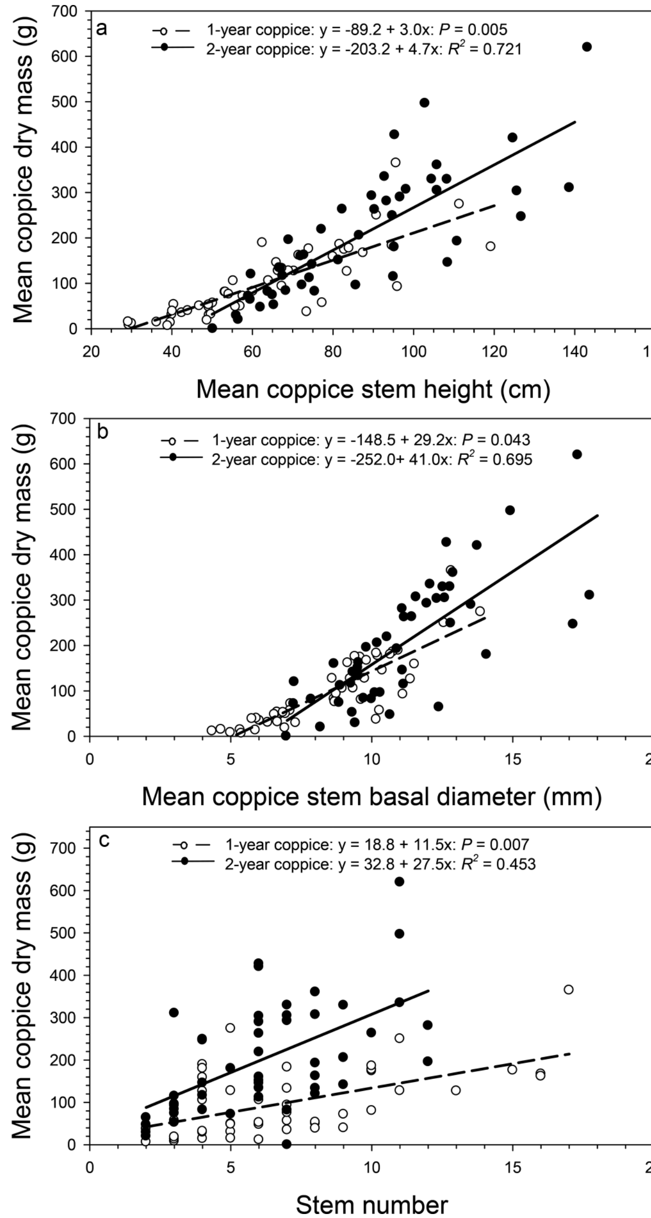


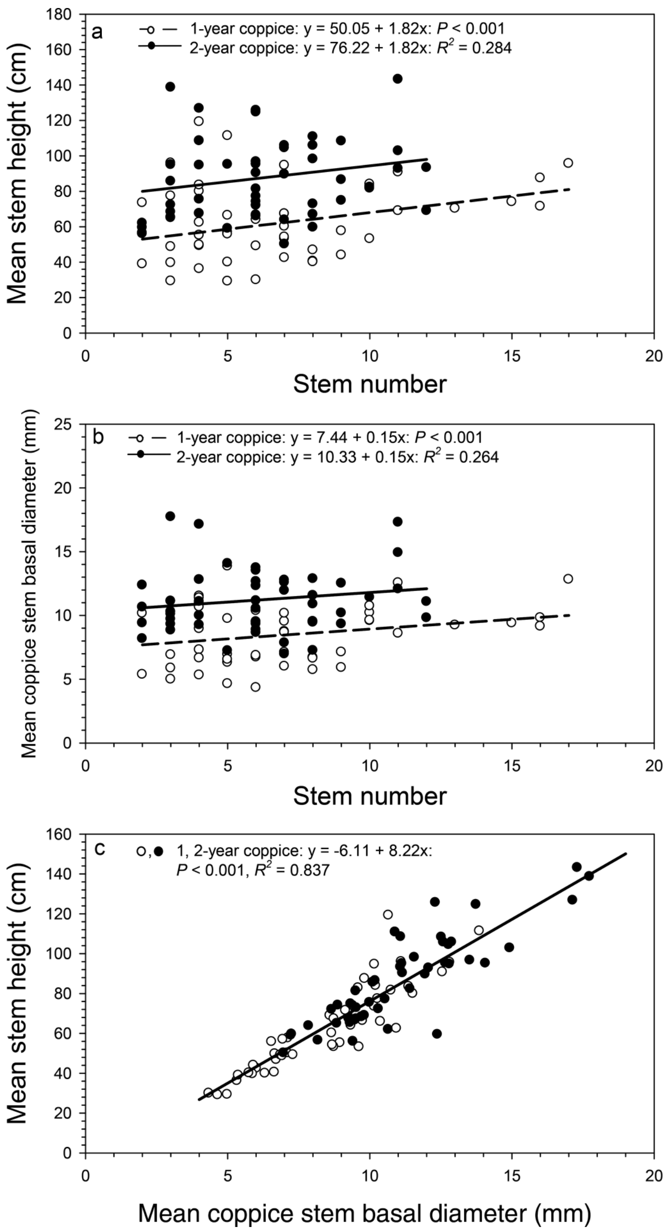
Fig. 4. Allometric relationships between mean coppice dry mass and (*a*) mean coppice stem height, (*b*) mean coppice stem basal diameter, and (*c*) coppice stem number for 1- and 2-year-old coppices.



tant factor in allometric relationships (Peichl and Arain 2007; Fatemi et al. 2011). The strength and consistency of the stem diameter–height relationship in coppice growth indicate that growth models developed for assessing biomass volume based on simple nondestructive measures may be useful for economic viability modeling (Ceulemans et al. 1996; Dillen et al. 2007; Rae et al. 2004).

Plants require N more than any other nutrient, and the positive effect of increased soil N on productivity globally is well known in the literature (Davidson et al. 2004; Elser et al. 2007; LeBauer and Treseder 2008). This bur oak experiment was randomly established on the infertile, treeless barrens of a former coal mine site where the soil N values were below 0.1% on four of the five site types; site type 5, however, had twice the soil N compared with the other four site types. The typical soil N values on floodplain sites

Fig. 5. Allometric relationships between (*a*) mean coppice stem height and coppice stem number, (*b*) mean stem basal diameter and coppice stem number, and (*c*) mean coppice stem height and mean coppice stem basal diameter for 1- and 2-year-old coppices.



associated with the Saint John River valley of NB, where bur oak occurs naturally, have not been determined, but it can be assumed that these sites are much more fertile due to depositions of silt following annual spring floods. These forests are also less exposed than the Salmon Harbour coal mine because bur oak generally occurs naturally in relatively closed forest stands on these floodplains. By assessing a number of key soil nutrients, our study demonstrated the positive effect of N on tree growth, especially on impoverished sites, where it appears that this N difference resulted in a 2.3-fold increase in aboveground biomass.

Coppicing has traditionally been viewed negatively by foresters, who believed it produced low-quality stems for timber; however, the young bur oak coppices in our study showed beneficial effects on tree stem structure. How long this beneficial effect maintains itself is uncertain. Potentially damaging wind exposure and drought conditions on such exposed treeless barrens probably resulted in initial slow growth and misshapen stems in the 10-year-old saplings prior to their harvesting. Harvesting and coppicing bur oak saplings at approximately 10 years or less appears useful in improving tree stem structure, either for timber quality or perhaps in shorter harvest rotations for bioenergy. The bur oak in our study responded well to coppicing, improving both tree stem structure and rapid recovery of biomass volume in young, slow-growing trees in which growth had been adversely affected by poor growing conditions. We, therefore, recommend coppicing as a means of rejuvenating young trees or saplings with growth and form that may have deteriorated under harsh growing conditions on highly disturbed sites such as those associated with mining operations.

Oak forests appear to be in decline globally, most often due to changing conditions with respect to drought (Kabrick et al. 2008; Allen et al. 2010; Fan et al. 2012; Gentilesca et al. 2017; Kotlarz et al. 2018; LeBlanc and Berland 2019). In many areas, it has been difficult to restore such forests under natural conditions using conventional forest management approaches due to drought, soil infertility, herbivory, and (or) vegetative competition (Kabrick et al. 2008; Hanberry and Nowacki 2016; Dey and Schweitzer 2018; Frank et al. 2018; Monteiro-Henriques and Fernandes 2018). Furthermore, doubts about the ability of older and larger oak stems to re-sprout vigorously following stem harvesting may have prevented a more widespread adoption of coppice management (Pyttel et al. 2013). The younger bur oak saplings in our study, however, have shown promising coppice regrowth following harvesting. The young bur oak saplings on this highly disturbed mine site showed excellent survival up to the age of 10 years following artificial establishment as seedlings, but the seedlings grew slowly (compared with adjacent naturally occurring *Populus tremuloides* Michx. and artificially established *Pinus rigida* Mill.), probably due to exposed site conditions and lack of water and nutrients. Harvesting such poorly growing saplings at a young age appears useful for promoting good-quality, coppice stem regrowth. This study will also establish opportunities to assess the longer term effects of coppicing on forest stand structure in an emerging bur oak forest, allowing us to clarify the effects of multi-stemmed coppices vs. single-stemmed bur oak trees as habitat for birds and other wildlife, as well as for production of bioenergy.

Conclusion

Coppicing appears to be an effective way to rejuvenate poorly formed, slow-growing stems on highly disturbed, infertile, exposed areas such as the treeless barrens of former mine sites. Coppicing may also be a pragmatic silvicultural alternative for maintaining species such as oaks in areas where they may currently be in decline due to changing environments resulting in increased drought. If drought becomes a major factor in oak decline, then coppicing in combination with shorter harvest cycles or rotations may be an effective way to maintain oak populations in such drought-prone areas because coppicing takes advantage of an established root system as opposed to re-establishing species by planting seedlings that may be more susceptible to drought following planting.

Acknowledgements

We gratefully acknowledge Ian DeMerchant for preparing the map in Fig. 1 and Judy Loo for contributions related to establishing this bur oak field study on the Salmon Harbour mine site. We also gratefully acknowledge useful comments on earlier versions of this manuscript from John Malcolm, Guy Larocque, and two anonymous reviewers.

References

Allen, D.A., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, L., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H. (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S.W., Semerci, A., and Cobb, N. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manage. **259**: 660–684.

Atwood, C.J., Fox, T.R., and Loftis, D.L. 2009. Effects of alternative silviculture on stump sprouting in the southern Appalachians. For. Ecol. Manage. **257**: 1305–1313. doi:10.1016/j.foreco.2008.11.028.

Beskardes, V., Keten, A., Kumbasli, M., Pekin, B., Yilmaz, E., Makineci, E., et al. 2017. Bird composition and diversity in oak stands under variable coppice management in northwestern Turkey. iForest, **11**: 58–63. doi:10.3832/ifor2489-010.

Ceulemans, R., McDonald, A.J.S., and Pereira, J.S. 1996. A comparison among eucalypt, poplar and willow characteristics with particular reference to a coppice growth modelling approach. Biomass Bioenerg. **11**(2–3): 215–231. doi:10.1016/0961-9534(96)00035-9.

Davidson, E.A., de Carvalho, C.J.R., Vieira, I.C.G., Figueiredo, R.O., Moutinho, P., Ishida, F.Y., et al. 2004. Nitrogen and phosphorus limitation of biomass growth in a tropical secondary forest. Ecol. Appl. **14** (Suppl. 4): S150–S163. doi:10.1890/01-6006.

DeGraaf, R.M., Hestbeck, J.B., and Yamasaki, M. 1998. Associations between breeding bird abundance and stand structure in the White Mountains, New Hampshire and Maine, U.S.A. For. Ecol. Manage. **103**: 217–233. doi:10.1016/S0378-1127(97)00213-2.

del Tredici, P. 2001. Sprouting in temperate trees: a morphological and ecological review. Bot. Rev. **67**: 121–140. doi:10.1007/BF02858075.

Dey, D.C., and Schweitzer, C.J. 2018. A review on the dynamics of prescribed fire, tree mortality, and injury in managing oak natural communities to minimize economic loss in North America. Forests, **9**: 461. doi:10.3390/f9080461.

Dillen, S.Y., Marron, N., Bastien, C., Ricciotti, L., Salani, F., Sabatti, M., et al. 2007. Effects of environment and progeny on biomass estimations of five hybrid poplar families grown at three contrasting sites across Europe. For. Ecol. Manage. **252**: 12–23. doi:10.1016/j.foreco.2007.06.003.

Elser, J.J., Bracken, M.E.S., Cleland, E.E., Gruner, D.S., Harpole, W.S., Hillebrand, H., et al. 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine, and terrestrial ecosystems. Ecol. Lett. **10**: 1135–1142. doi:10.1111/j.1461-0248.2007.01113.x.

Fan, Z., Fan, X., Crosby, M.K., Moser, W.K., He, H., Spetich, M.A., and Shifley, S.R. 2012. Spatio-temporal trends in oak decline and mortality under periodic regional drought in the Ozark highlands of Arkansas and Missouri. Forests, **3**: 614–631.

Fang, S., Liu, S., Cao, Y., Liu, D., Yu, M., and Tang, L. 2011. Sprout development, biomass accumulation and fuelwood characteristics from coppiced plantations of *Quercus acutissima*. Biomass Bioenerg. **35**: 3104–3114. doi:10.1016/j.biombioe.2011.04.017.

Farrar, J.L. 1995. Trees in Canada. Fitzhenry and Whiteside Ltd. and the Canadian Forest Service, Ottawa, Ontario, Canada.

Fatemi, F.R., Yanai, R.D., Hamburg, S.P., Vadeboncoeur, M.A., Arthur, M.A., Briggs, R.D., and Levine, C.R. 2011. Allometric equations for young northern hardwoods: the importance of age-specific equations for estimating aboveground biomass. Can. J. For. Res. **41**(4): 881–891. doi:10.1139/x10-248.

Frank, G.S., Rathfon, R.A., and Saunders, M.R. 2018. Ten-year response of underplanted northern red oak to silvicultural treatments, herbivore exclusion, and fertilization. Forests, **9**: 571. doi:10.3390/f9090571.

Fuller, R.J., and Henderson, A.C.B. 1992. Distribution of breeding songbirds in Bradfield Woods, Suffolk, in relation to vegetation and coppice management. Bird Study, **39**: 73–88. doi:10.1080/00063659209477103.

Gargaglione, V., Peri, P.L., and Rubio, G. 2008. Allometric relationships for biomass partitioning of *Nothofagus antarctica* trees of different crown classes over a site quality gradient. For. Ecol. Manage. **259**: 1118–1126. doi:10.1016/j.foreco.2009.12.025.

Gentilesca, T., Camarero, J.J., Colangelo, M., Nole, A., and Ripullone, F. 2017. Drought-induced oak decline in the western Mediterranean region: an overview on current evidences, mechanisms and management options to improve forest resilience. iForest Biogeosc. For. **10**: 796–806. doi:10.3832/ifor2317-010.

Gilman, E.F., and Watson, D.G. 1994. *Quercus macrocarpa*, bur oak [online]. USDA Forest Service, Fact Sheet ST-551. Available from: http://www.forestry.ok.gov/Websites/forestry/Images/trees,buroak.pdf.

Gracia, M., and Retana, J. 2004. Effect of site quality and shading on sprouting patterns of holm oak coppices. For Ecol. Manage. **188**: 39–49. doi:10.1016/j.foreco.2003.07.023.

Hanberry, B.B., and Nowacki, G.J. 2016. Oaks were the historical foundation genus of the east-central United States. Quat. Sci. Rev. **145**: 94–103. doi:10.1016/j.quascirev.2016.05.037.

Hinds, H.R. 1986. Flora of New Brunswick. Primrose Press, Fredericton, N.B., Canada.

Johnson, P.S. 1990. *Quercus macrocarpa*, Michx., bur oak, *Fagaceae*, Beech family. *In* Silvics of North America, Volume 2, Hardwoods. *Edited by* R.M. Burns and B.H. Honkala. USDA Forest Service, Washington, D.C., Agriculture Handbook 654. pp. 686–692.

Kabrick, J.M., Dey, D.C., Jensen, R.G., and Wallendorf, M. 2008. The role of environmental factors in oak decline and mortality in the Ozark Highlands. For. Ecol. Manage. **255**: 1409–1417. doi:10.1016/j.foreco.2007.10.054.

Koeper, G.J., and Richardson, C.J. 1980. Biomass and net primary production regressions for *Populus grandidentata* on three sites in northern lower Michigan. Can. J. For. Res. **10**(1): 92–101. doi:10.1139/x80-015.

Kotlarz, J., Nasilowska, S.A., Rotchimmel, K., Kubiak, K., and Kacprzak, M. 2018. Species diversity in oak stands and its significance for drought resistance. Forests, **9**: 126. doi:10.3390/f9030126.

Labrecque, M., and Teodorescu, T.I. 2005. Field performance and biomass production of 12 willow and poplars in short-rotation coppice in southern Quebec (Canada). Biomass Bioenerg. **29**(1): 1–9. doi:10.1016/j.biombioe.2004.12.004.

LeBauer, D.S., and Treseder, K.K. 2008. Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. Ecology, **89**: 371–379. doi:10.1890/06-2057.1.

LeBlanc, D.C., and Berland, A.M. 2019. Spatial variation in oak (*Quercus* spp.) radial growth responses to drought stress in eastern North America. Can. J. For. Res. **49**: 986–993. doi:10.1139/cjfr-2018-0360.

Lockhart, B.R., and Chambers, J.L. 2007. Cherrybark oak stump sprout survival and development five years following plantation thinning in the lower Mississippi alluvial valley, U.S.A. New For. **33**: 183–192. doi:10.1007/s11056-006-9022-7.

Martin, Š., Daniel, V., Aytekin, E., and Radim, M. 2015. The effect of coppice management on the structure, tree growth and soil nutrients in temperate Turkey. J. For. Sci. **61**: 27–34. doi:10.17221/91/2014-JFS.

McKeague, J.A. 1978. Manual on soil sampling and methods of analysis. 2nd ed. Canadian Society of Soil Science, Ottawa, Ontario, Canada.

McPhee, D.A. 2001. The bur oak, *Quercus macrocarpa*, of New Brunswick: a species distribution and comparative genetic diversity study. M.Sc. thesis, University of New Brunswick.

McPhee, D.A., and Loo, J.A. 2009. Past and present distribution of New Brunswick bur oak populations: a case for conservation. Northeast. Nat. **16**: 85–100. doi:10.1656/045.016.0107.

Monteiro-Henriques, T., and Fernandes, P.M. 2018. Regeneration of native forest species in mainland Portugal: identifying main drivers. Forests, **9**: 694. doi:10.3390/f9110694.

Mosseler, A., and Major, J.E. 2016. Allometric relationships in coppice biomass structure of seven North American willow (*Salix*) species. Biomass Bioenerg. **88**: 97–105. doi:10.1016/j.biombioe.2016.03.025.

Mosseler, A., Major, J.E., and Labrecque, M. 2014*a*. Growth and survival of seven native willow species on highly disturbed coal mine sites in eastern Canada. Can. J. For. Res. **44**(4): 340–349. doi:10.1139/cjfr-2013-0447.

Mosseler, A., Major, J.E., Labrecque, M., and Larocque, G.R. 2014*b*. Allometric relationships in coppice biomass production for two North American willows (*Salix* spp.) across three different sites. For. Ecol. Manage. **320**: 190–196. doi:10.1016/j.foreco.2014.02.027.

Mullerova, J., Szabo, P., and Hedl, R. 2014. The rise and fall of traditional forest management in southern Moravia: a history of the past 700 years. For. Ecol. Manage. **331**: 104–115. doi:10.1016/j.foreco.2014.07.032.

Mullerova, J., Hedl, R., and Szabo, P. 2015. Coppice abandonment and its implications for species diversity in forest vegetation. For. Ecol. Manage. **343**: 88–100. doi:10.1016/j.foreco.2015.02.003.

Paul, K.I., Roxburgh, S.H., Ritson, P., Brooksbank, K., England, J.R., Larmour, J.S., et al. 2013. Testing allometric equations for prediction of above-ground biomass of mallee eucalypts in southern Australia. For. Ecol. Manage. **310**: 1005–1015. doi:10.1016/j.foreco.2013.09.040.

Peichl, M., and Arain, M. 2007. Allometry and partitioning of aboveground and belowground tree biomass in an age-sequence of white pine forests. For. Ecol. Manage. **253**(1–3): 68–80. doi:10.1016/j.foreco.2007.07.003.

Perkins, D., Uhl, E., Biber, P., du, Toit, B., Carraro, V., Rotzer, T., and Pretzsch, H. 2018. Impact of climate trends and drought events on the growth of oaks (*Quercus robur* L. and *Quercus petraea* (Matt) Liebl.) within and beyond their natural range. Forests, **9**: 108. doi:10.3390/f9030108.

Pyttel, P.L., Fischer, U.F., Suchomel, C., Gartner, S.M., and Bauhus, J. 2013. The effect of harvesting and stump mortality and re-sprouting in aged oak coppice forests. For. Ecol. Manage. **289**: 18–27. doi:10.1016/j.foreco.2012.09.046.

Rae, A.M., Robinson, K.M., Street, N.R., and Taylor, G. 2004. Morphological and physiological traits influencing biomass productivity in short-rotation coppice poplar. Can. J. For. Res. **34**(7): 1488–1498. doi:10.1139/x04-033.

Schnabel, A., and Hamrick, J.L. 1990. Comparative analysis of population genetic structure in *Quercus macrocarpa* and *Q. gambelii* (Fagaceae). Syst. Bot. **15**: 240–251. doi:10.2307/2419179.

Stojanović, M., Sánchez-Salguero, R., Levanič, T., Szatniewska, J., Pokorný, R., and Linares, J.C. 2017. Forecasting tree growth in coppiced and high forests in the Czech Republic. The legacy of management drives the coming *Quercus petraea* climate responses. For. Ecol. Manage. **405**: 56–68. doi:10.1016/j.foreco.2017.09.021.

Svátek, M., and Matula, R. 2015. Fine-scale spatial patterns in oak sprouting and mortality in a newly restored coppice. For. Ecol. Manage. **348**: 117–123. doi:10.1016/j.foreco.2015.03.048.

Ter-Mikaelian, M.T., and Korzukhin, M.D. 1997. Biomass equations for sixty-five North American tree species. For. Ecol. Manage. **97**: 1–24. doi:10.1016/S0378-1127(97)00019-4.

Vild, O., Rolecek, J., Hedl, R., Kopecky, M., and Utinek, D. 2013. Experimental restoration of coppice-with-standards: response of understorey vegetation from the conservation perspective. For. Ecol. Manage. **310**: 234–241. doi:10.1016/j.foreco.2013.07.056.

Volk, T.A., Abrahamson, L.P., Nowak, C.A., Smart, L.B., Tharakan, P.J., and White, E.H. 2006. The development of short-rotation willow in the northeastern United States for bioenergy and bio-products, agroforestry and phytoremediation. Biomass Bioenerg. **30**: 715–727. doi:10.1016/j.biombioe.2006.03.001.

Vrska, T., Motta, R., and Mosseler, A. (*Editors*). 2016. Is there a place for coppicing as a silvicultural system in the 21st century? *In* iForest Special Issue "Coppice forests: past, present and future" [online]. Available from: www.sisef.it/iforest/pdf/COPCZ_introduction.pdf.

Xue, Y., Zhang, W., Zhou, J., Ma, C., and Ma, L. 2013. Effects of stump diameter, stump height, and cutting season on *Quercus variabilis* stump sprouting. Scand. J. For. Res. **28**: 223–231. doi:10.1080/02827581.2012.723742.

Zipper, C.E., Burger, J.A., Skousen, J.G., Angel, P.N., Barton, C.D., Davis, V., and Franklin, J.A. 2011. Restoring forests and associated ecosystem services on Appalachian coal surface mines. Environ. Manage. **47**: 751–765. doi:10.1007/s00267-011-9670-z.