Forests **2012**, *3*, 528-545; doi:10.3390/f3030528

OPEN ACCESS

forests

ISSN 1999–4907

www.mdpi.com/journal/forests

Article

The Sprouting Capacity of 8–21-Year-Old Poplars and Some Practical Implications

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Received: 31 May 2012; in revised form: 5 July 2012 / Accepted: 6 July 2012 / Published: 24 July 2012

Abstract: We investigated the sprouting capacity of poplar stumps in ten 8–21-year old stands growing on former farmland in Sweden situated between 55°N and 60°N. Seven of the stands were planted with the clone OP-42 (*Populus maximowiczii* Henry × *Populus trichocarpa* Torr. and Gray), one with black cottonwood (*Populus trichocarpa* Torr. and Gray) and two with unidentified clones. The poplars' mean age was 17 years (range 8–21); six of the stands were growing on clay soils, two on tills and two on loam. The studied sprouts were 1–7 years old. Stump sprouting was observed in all studied stands. The number of sprouts per living stump decreased as sprout age increased. The mean dry mass of all sprouts stump^{-1} was 16.1 ± 14.0 (range 3.3–37.2) kg. A biomass equation was constructed for estimating sprout biomass from the sprouts' diameter at 10 cm above the ground (D_{10}). The mean total sprout weight per hectare for sprouts amounted to 16.9 ± 14.6 (range 1.2–41.3) tons ha^{-1} when calculated for the actual living stumps in the studied areas.

Keywords: diameter; height; poplar; sprout; sprout age; sprout dry mass; sprouting capacity

1. Introduction

To date, poplar plantations in Sweden have been managed with the aim of promoting the establishment of seedlings (cuttings), protecting them against damage caused by wild animals (moose, deer and roe deer) and ensuring that stands reach an age that makes them suitable for thinning and final cutting. The total area planted with poplar in Sweden is small (<1000 ha), and Swedish demand for poplar products (timber and pulp wood) is uncertain. At present, most harvested poplars are sold to thermal power stations as biomass, with a smaller quantity going to pulp mills as pulp wood. Most current poplar stands are around 15–25 years old and their owners are interested in harvesting them.

The most common methods for establishing new poplar stands under conditions such as those found in Sweden are:

- Planting;
- Managing the sprouts on the stumps for biomass and/or pulp wood and timber production;
- Removing the stumps after harvesting the stand cf. [1] and planting.

Poplar reproduces vegetatively by sprouting from its stumps and also by growing suckers from its roots. Black cottonwood (*Populus trichocarpa* Torr. and Gray) commonly produces sprouts while balsam poplar produces both sprouts and suckers [2]. Suckers are less common on gravel soil types than on silty soils. Sprout biomass production is dependent on a range of factors, including soil conditions, the overall growth rate, and the number of sprouts per stump. In a study on a 6-year-old coppice that included 17 clones, the observed rates of biomass production ranged from 2 to 11 tons ha^{-1} year^{-1} d. w. [3]. However clones with high biomass production could be sensitive to different abiotic factors. It was therefore proposed that a mixture of clones should be planted to minimize the risk of generating a stand with a low sprouting capacity. When growing sprouts for pulp wood or timber production, it is necessary to ensure that the number of sprouts per stump does not exceed one or two; if this is not done, competition among the sprouts will reduce stem dimensions and the harvested trees will be too small for pulp wood or timber production [4]. According to Stanturf *et al.* [4], the level of management needed to accomplish this is not cost effective for small landowners because the stand must be entered twice.

Previous studies on poplar sprouting have mostly focused on young poplars (2–10 years old). The rotation period might contain two or three coppice during 3–4 years each. However, despite demand from Swedish forest owners, there is little information on the management of poplar sprout growth for biomass production when working with older (15–20 years) trees that have recently been harvested. Coppicing is not widely used in Sweden for tree species other than *Salix* grown using short rotations, and there is little collective practical experience with or knowledge of sprout management.

Many factors influence a stump's ability to sprout. According to Lust and Mohammady [5], these include the tree species in question, the dimensions (and thus age) of the stump, the season in which the tree was cut, and the site conditions. The most important factors in terms of coppice regeneration are the age of the harvested stand and the time of year in which they were harvested. According to Stanturf *et al.* [4], trees should be harvested before they are 10 years old in order to maximize the extent of sprouting. In most studies on the relationship between felling time and sprouting ability, it has been found that the stumps of trees felled during the growing season produce the shortest and fewest sprouts [6]. This may be because the levels of starch and soluble carbohydrates in the roots are low during the growing season [7]. Harvesting should therefore be conducted in the winter or spring if the aim is to maximize the rate of sprouting [8,9]. After harvesting, the stumps of the poplar stand may start to produce sprouts. The frequency of sprouting depends on the clone in question, the season during which harvesting was conducted, and the stump height—taller stumps (30 cm) have been reported to produce more sprouts per living stump than shorter ones (10 cm) [9]. These findings were confirmed in a study reported by Crist *et al.* [10], who noted that 46 cm tall stumps produced more sprouts than those that were 8 or 15 cm tall.

Coppicing has been widely adopted as a management technique for biomass production because the early growth rate of sprouts is greater than that of seedlings or cuttings [11,12]. Sprouts develop from dormant buds, which are released following hormonal suppression when a tree is cut [13,14]. Sprouts emerge on the vertical side of the stump above ground level and to some extent below ground level <5 cm [15]. However sprouts that originate too far above ground level are subject to breakage [16]. While the literature contains few discussions of coppicing harvested poplars, Dryck and Stroble [17] report that a paper mill company once subjected poplar stands to two coppice rotations following an initial harvest at 12 years of age.

The aim of the study reported herein was to investigate the sprouting potential and biomass production of poplar stumps with one to seven year old sprouts. A biomass equation for estimating sprouts' dry mass based on their diameter 10 cm above the ground (D_{10}) was developed. The studied poplar stands were 8 to 21 years old. In addition to stump survival, the number of sprouts per living stump, the heights and diameters of sprouts with different ages, and the sprouts' biomass were recorded.

2. Materials and Methods

2.1. Study Site

Ten clear cut 8–21-year old poplar stands growing on former farmland located between latitudes 56° and 60°N in Sweden (Figure 1 and Table 1) were examined. These stands are some of the first poplar stands planted in Sweden during the period when former farmland was reforested at the end of the 1980s. The rate and which the stands grew prior to cutting and the extent of damage they had sustained were assessed on the basis of information provided by the forest owner. Seven of the stands were planted with the clone OP-42 (*Populus maximowiczii* Henry × *Populus trichocarpa* Torr. and Gray), one with black cottonwood (*Populus trichocarpa* Torr. and Gray) and two with unidentified clones. The stands' had been clear cut within 7 years of the study period. Stand no. 8 (4-year-old sprouts) was re-measured when the sprouts were 7 years old (stand No. 9). All cutting had been performed between October and March.

2.2. Methods

The stands' properties prior to clear cutting are presented in Table 1 and were discussed in detail in a previous publication [18]. In each of the ten locations a plot containing 100 stumps (10 rows, each containing ten stumps) was chosen; see Figure 2.

Figure 1. Locations of the study sites, all of which were located on abandoned farmland in Sweden.

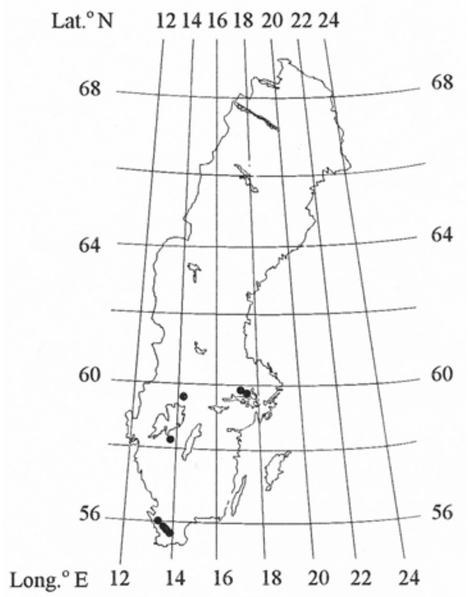


Table 1. Properties of the hybrid poplar stands prior to clear cutting.

Stand No.	Age, years	DBH, mm Mean ± SD	Height, m Mean ± SD	No. of Stems ha^{-1}	Basal area, m^2 ha^{-1}	Soil type	Variety [a]
1	21	330 ± 81	29.2 ± 2.0	361	30.9	Light clay	3
Range		119–574	21.6–32.9				
2	8	82 ± 30	12.8 ± 3.0	2143	11.3	Light clay	3
Range		50–255	7.5–22.2				
3	18	289 ± 49	25.5 ± 1.1	828	54.3	Light clay	1
Range		221–371	23.0–27.7				
4	19	246 ± 40	25.1 ± 1.1	1250	59.4	Medium clay	2
Range		68–431	19.2–27.0				
5	20	246 ± 30	24.4 ± 0.8	1110	52.8	Sandy-Silty till	2
Range		203–300	23.1–26.0				
6	21	251 ± 53	24.5 ± 1.6	1200	59.4	Light clay	2
Range		149–388	21.1–26.7				
7	19	281 ± 40	24.0 ± 0.7	675	37.8	Medium clay till	2
Range		194–356	22.8–25.0				
8	14	217 ± 44	23.4 ± 4.0	1111	41.1	Sandy loam	2
Range		118–298	8.4–29.8				
9	14	217 ± 44	23.4 ± 4.0	1111	41.1	Sandy loam	2
Range		118–298	8.4–29.8				
10	20	283 ± 40	25.8 ± 1.1	707	35.0	Medium clay	2
Range		197–367	23.0–27.7				
Mean ± SD	17 ± 4	244 ± 67	23.8 ± 4.2	1050 ± 477	42.3 ± 14.9		
Range	8–21	82–330	12.8–29.2	361–2143	11.3–59.4		

[a]: 1. (*P. trichocarpa* Torr. and Gray); 2. OP-42 (*P. maximowiczii* Henry × *P. trichocarpa* Torr. and Gray); 3. Unknown.

Figure 2. Sampling of sprouts.

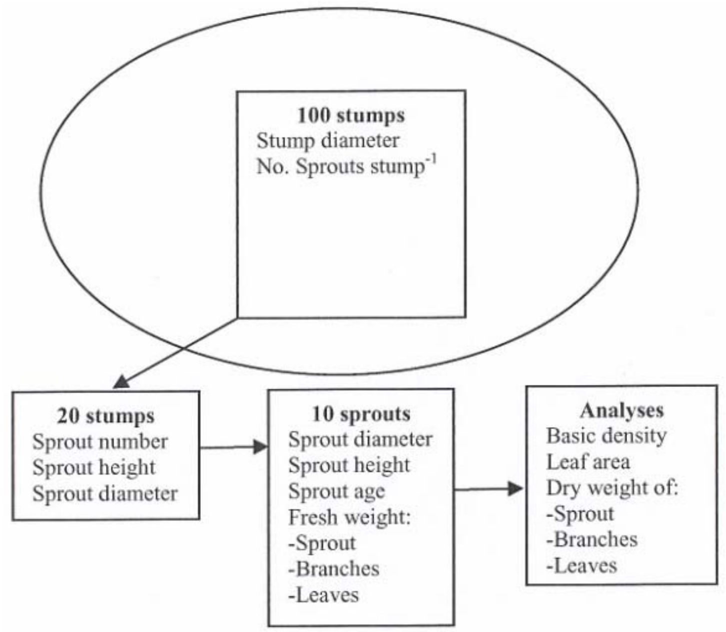


Table 2. Mean stump diameters and properties of the sampled stumps and sprouts.

Stand No.	Stump diameter, mm	Living, % [a]	Sprout			
			Age, years	No. of sprouts (living stump^{-1})	Diameter (0.1 m), mm	Height, m
1	319 ± 70	80	1	18	10 ± 7	1.03 ± 0.57
Range	193–432			2–55	3–29	0.35–2.45
2	90 ± 34	76	3	4	37 ± 11	3.53 ± 0.64
Range	47–290			1–14	21–70	2.50–4.60
3	321 ± 51	57	5	7	64 ± 30	6.19 ± 2.11
Range	225–425			1–14	15–120	1.80–9.20
4	333 ± 55	79	1	37	10 ± 4	1.15 ± 0.34
Range	192–463			8–68	6–26	0.63–2.35
5	276 ± 30	70	6	3	85 ± 35	7.00 ± 1.81
Range	229–302			1–8	27–149	3.80–9.50
6	284 ± 62	86	2	18	26 ± 12	2.36 ± 0.74
Range	154–445			7–43	12–80	0.84–4.70
7	342 ± 50	100	1	35	11 ± 3	1.12 ± 0.28
Range	154–445			20–51	6–26	0.358–1.98
8	250 ± 39	95	4	8	49 ± 25	5.52 ± 2.10
Range	165–319			1–20	7–107	1.40–10.00
9	239 ± 39	86	7	4	76 ± 33	6.89 ± 2.11
Range	180–320			1–12	29–158	3.50–11.90
10	299 ± 49	90	1	27	12 ± 4	1.04 ± 0.32
Range	152–390			11–46	6–28	0.41–2.01
Mean ± SD	275 ± 74	82 ± 13	3 ± 3	16 ± 13	38 ± 29	3.58 ± 2.11
Range	90–342	57–100	1–7	3–37	10–85	1.03–7.00

[a]: Percentage of living stumps per 100 stumps examined.

The number of stumps with and without sprouts, the stumps' diameters, and the number of sprouts per stump were recorded (Table 2). The sprout age was determined by counting the annual rings in the sprout base combined with the information about date for clear cutting by the owner. In addition, for every fifth stump with sprouts (20 stumps in total), the diameter 10 cm (D_{10}) above their point of origin on the stump (mm) and height (m) were measured. Both the diameter at 0.1 m and breast height (DBH) was measured on sprouts ≥3 years old and ≥2 m and added to the data. If a sampled stump had no sprouts, those on the closest stump with sprouts in the same row were measured instead.

The distribution of the sprouts' diameters was analyzed and ten separate diameter classes were identified. One sprout from each class was then cut and subjected to further measurements (Figure 2). The total aboveground biomass for individual poplar trees and total stem biomass were estimated using the biomass equation of Johansson and Karačić [18]. The fresh weight of the sprouts (stem, branches and leaves) was recorded in the field (Table 3). The dry mass as a percentage of the fresh weight was calculated for the stem + branches and leaves based on the sample data. A sample of 50 leaves was collected from each sprout for laboratory analysis; if a sprout had <50 leaves, all of its leaves were taken. 10 cm sections of each sprout were taken at a height of 0.5 m in order to estimate their basic wood density.

Table 3. Fresh and dry mass production (kg) and mean percentage of total sprout weight.

Fresh weight (kg)				**Dry weight (kg)**			
Total	**Stem**	**Branches**	**Leaves**	**Total**	**Stem**	**Branches**	**Leaves**
8.76 ± 13.45	5.18 ± 7.93	0.87 ± 1.60	2.70 ± 4.44	4.25 ± 6.57	2.51 ± 3.87	0.42 ± 0.78	1.31 ± 2.20
0.12–56.73	0.07–29.93	0.01–10.38	0.01–21.93	0.06–29.12	0.03–14.97	0.01–5.09	0.01–11.62
Percentage of total fresh weight (%)				**Percentage of total dry weight (%)**			
Mean ± SD	60 ± 6	8 ± 3	32 ± 8	Mean ± SD	60 ± 7	8 ± 3	32 ± 8
Range	45–79	3–21	9–46	Range	49–80	2–23	7–44

2.3. Basic Density Analysis

The basic density of the stems was estimated using the water-immersion method described by Andersson and Tuimala [19]. Samples of sprout stems without bark were saturated in water for 24 h and then weighed (g), after which their volume (cm^3) was determined. The dry mass (g) of the samples was determined after drying at 105 °C in an air-ventilated oven for 3–5 days, depending on sample dimensions. The basic densities of the debarked stem samples (g cm^{-3}) were then calculated as the ratio of their dry weight to their fresh volume.

2.4. Leaf Analyses

The sampled leaves were weighed fresh. The projected leaf area (PLA) in cm^2 was determined with a leaf area meter (LI-3000, LI-COR. Inc. Lincoln, USA). Each sample was then dried at 105 °C in an oven for 48 h and weighed. The dry mass of all leaves was then calculated. The specific leaf area (SLA) for each sprout was calculated as its total leaf area (cm^2) divided by the dry weight of all its leaves combined (g).

2.5. Soil Analysis

The soil types for the studied stands were analyzed in a previously reported study by Johansson and Karačić [18]. Four of the ten stands were growing on light clay soils, two on medium clay soils, two on sandy loams, and two on till soils (Table 1).

2.6. Data Analysis

The dry mass production per sprout (total, stem, branches and leaves) was calculated using an equation that describes the correlation between sprout diameter (mm) at a height of 10 cm (D_{10}) and dry mass production (kg) that was derived by fitting to the data collected for the measured sprouts.
The following power function was tested:

$$M = \beta_0 D^{\beta 1} \quad (1)$$

Where M = dry mass, (kg sprout^{-1}, stem + branches^{-1} or leaves^{-1}); D_{10} = sprout diameter at a height of 10 cm (over bark (ob); mm); β_0 and β_1 are parameters.

Power models are frequently used to describe such relationships [20–24]. The actual dry mass production of each sprout examined was then estimated on the basis of its D_{10} value.

Data were analyzed by nonlinear regression using the SAS/STAT system for personal computers [25]. The fit of the nonlinear regressions was assessed using the coefficient of determination [26]:

$$R^2 = 1 - (\text{SSE/SST (No. of observations)}) \quad (2)$$

where SSE is $\sum_{i=1}^{n} (w_i - \overline{w}_i)^2$ and SST is $\frac{1}{n} \sum_{i=1}^{n} (w_i - \hat{w}_i)^2$.

The quality of the regression was also tested using the root mean squared error (RMSE).

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(w - \hat{w}_i)^2}{n}} \quad (3)$$

where w_i, $\overline{w}_i$ and $\hat{w}_i$ are observed, mean and predicted weights (w).

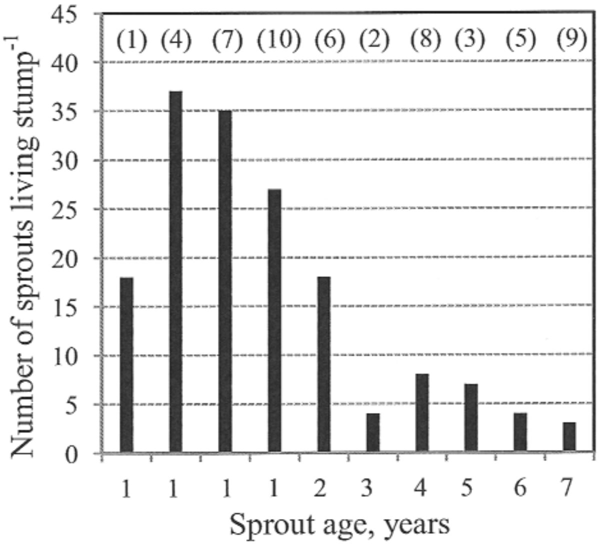
Throughout this paper, means are presented together with the associated standard deviation (SD).

3. Results

3.1. Sprout Characteristics

The number of sprouts varied depending on stump diameter. Stumps ≤ 200 mm produced less than 20 sprouts per stump. The sprout number for larger stumps (≥200 mm) varied between 1 and 68 with a wide spreading. The number of sprouts per living stump varied depending on sprout age and decreased as sprout age increased cf. stand No. 2 (Figure 3). There are no correlation between soil type and sprouting capacity. The stumps with the youngest produced (one year old) produced 18–37 sprouts per living stump (range 2–68) while stumps with 7 years old sprouts had 3 (1–12) sprouts. The mean D_{10} values and heights of the youngest sprouts were 10–12 mm and 1.03–1.12 m, respectively. Diameter for sprouts ≥3 years old and >2 m tall were converted to estimate D_{10} values. A simple regression between DBH and 0.1 m values was constructed: DBH = $D_{10}/1.35$. The oldest sprouts had D_{10} values of 76–85 mm and heights of 6.89–7.00 m (Table 2).

Figure 3. Number of sprouts per living stump as a function of sprout age. Location numbers are shown in parentheses.



3.2. Biomass of Sample Sprouts

The mean dry mass of a sprout was 4.25 ± 6.57 (0.06–29.12), stem 2.51 ± 3.87 (0.03–14.97), branches 0.42 ± 0.78 (0.01–5.09) and leaves 1.31 ± 2.20 (0.01–11.62) kg (Table 3). As percentages of the total fresh weight, the dry mass contents of sprouts, stems, branches and leaves were 48 ± 4 (33–68), 48 ± 5 (37–66), 48 ± 3 (43–67) and 48 ± 6 (33–59)%, respectively. The dry weight of the stem accounted for 60 ±7 (49–80) % of the total dry mass of the sprout, with branches and leaves representing 8 ± 3 (2–23)% and 32 ± 8 (7–44)%, respectively (Table 3). The mean dry mass of sprouts per living stump was 16.07 ± 13.97 (3.27–37.22) kg and the mean annual increase in sprout dry mass (MAI) was 4.80 ± 1.48 kg (1.93–7.02) stump^{-1} year^{-1} (Table 4). The mean basic density of sprouts at the ten different locations ranged from 0.200 and 0.467 g cm^{-3} with a mean of 0.323 ± 0.012 (Table 5).

3.3. Leaf Characteristics

Leaves accounted for a greater proportion of the total dry mass of the sprouts than did branches. The mean weight per leaf was 0.65 ± 0.18 (0.14–2.11) g (Table 5) and the total dry weight of leaves per sprout was 1.31 kg, ranging from 0.01 to 11.62 kg (Table 3). The mean PLA was 50 (13–143) cm^2 and the mean SLA was 85 (36–200) cm^2 g^{-1} d. w.

Table 4. Mean and range of dry mass (kg) and MAI of sprouts per living stump.

Stand No.	Age, years	Sprout age, years	Weight, kg	MAI
1	21	1	3.27 ± 1.62	3.27
Range			1.72–7.02	
2	8	3	5.79 ± 6.32	1.93
Range			1.25–24.24	
3	18	5	35.12 ± 15.29	7.02
Range			11.22–65.88	
4	19	1	4.75 ± 3.03	4.75
Range			0.99–12.34	
5	20	6	37.22 ± 26.90	4.65
Range			2.79–73.41	
6	21	1	10.22 ± 4.49	5.11
Range			3.69–17.73	
7	19	1	6.82 ± 1.86	6.82
Range			3.88–9.41	
8	14	4	19.57 ± 9.45	4.89
Range			4.91–37.95	
9	14	7	33.12 ± 14.84	4.73
Range			9.91–57.65	
10	20	1	4.83 ± 1.69	4.83
Range			2.30–9.50	
Mean	17 ± 4		16.07 ± 13.97	4.80 ± 1.48
Range	8–21	1–7	3.27–37.22	1.93–7.02

Table 5. Dry weight data for individual leaves (g), total dry weight of leaves per sprout (g), number of leaves per sprout, projected leaf area (PLA; cm^2), specific leaf area (SLA; cm^2 g^{-1}) and basic density (g cm^{-3}) for sample sprouts. All values quoted are means ± SD; *n*=10.

	Weight d. w. g leaf	No. of leaves sprout^{-1}	PLA (cm^2)	SLA (cm^2 g^{-1} d.w.)	Basic density (g cm^{-3})
Mean ± SD	0.65 ± 0.18	2,053 ± 2,889	50 ± 14	85 ± 25	0.323 ± 0.012
Range	0.14–2.11	3–15,092	13–143	36–200	0.200–0.467

3.4. Dry Mass Function for Sprouts

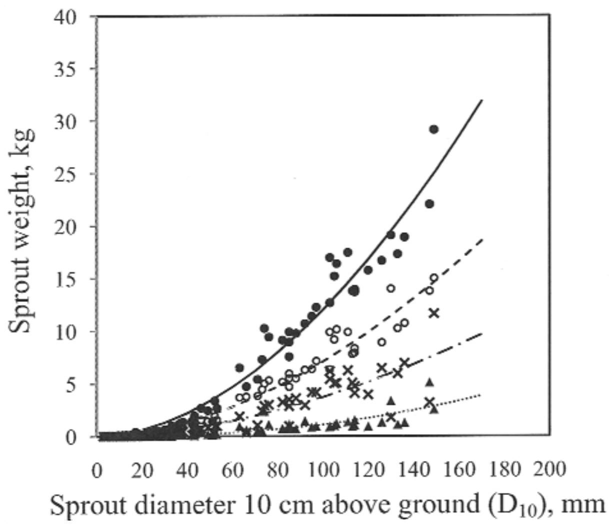
Function (1) was adjusted to fit the dry mass data as a function of sprout stem diameter (D_{10}) for all stump sizes. The agreement between the fitted function and the experimental curves for the dry masses of sprouts, stems, branches and leaves were statistically and practically acceptable (Table 6).

The coefficient of determination (R^2) and RMSE values both indicated that the fitted curves were in good agreement with the experimental results. Curves showing the relationships between D_{10} and the dry masses of the sprouts as a whole and the sprouts' stems, branches, and leaves are presented in Figure 4.

Table 6. Estimated parameters of equation (1) for estimating the dry weight of hybrid poplar sprouts growing on former farmland.

Components	Parameter	Parameter estimates	Standard errors of parameters	R^2	RMSE	Pr > F
Total	β_0	0.002570	0.000769	0.98	1.1650	<0.0001
	β_1	1.835000	0.062900			
Stem	β_0	0.001720	0.000624	0.97	0.8432	<0.0001
	β_1	1.808000	0.076100			
Branches	β_0	0.000026	0.000041	0.70	0.5111	<0.0001
	β_1	2.318000	0.332000			
Leaves	β_0	0.000975	0.000725	0.87	0.9155	<0.0001
	β_1	1.791700	0.015650			

Figure 4. Dry mass per sprout (kg sprout^{-1}) as a function of diameter at 10 cm above ground (D_{10}), mm of total (——), stem (- - - -), branches (— · —) and leaves (..........) for sampled poplar stump sprouts growing on abandoned farmland.



3.5. Stand Characteristics

The dry mass production per hectare was calculated using the experimental data on the mean weight of sprouts per living stump (Table 4) and the number of stumps per hectare at the studied locations (Table 1). The mean dry mass was 16.9 ± 14.6 (range: 1.2–41.3) tons ha^{-1} and the MAI was 4.7 ± 1.5 (1.2–6.1) tons ha^{-1} year^{-1} (Table 7). Because the stands were relatively old and had a large number of stems per hectare in some cases, biomass calculations were based on 1000 stems per hectare. The mean dry mass production was 19.1 ± 20.3 (3.3–37.2) tons ha^{-1} and the MAI was 4.8 ± 1.5 (1.9–7.0) tons ha^{-1} year^{-1}.

Table 7. Dry mass production of sprouts per living stump, tons ha^{-1}.

Stand No.	Sprout age, years	Dry mass [a]	MAI	Dry mass [b]	MAI
1	1	1.2	1.2	3.3	3.3
2	3	12.4	4.1	5.8	1.9
3	5	29.1	5.8	35.1	7.0
4	1	5.9	5.9	4.8	4.8
5	6	41.3	5.2	17.2	4.7
6	2	12.3	6.1	10.2	5.1
7	1	4.6	4.6	6.8	6.8
8	4	21.7	5.4	19.6	4.9
9	7	36.8	5.3	33.1	4.7
10	1	3.4	3.4	4.8	4.8
Mean		16.9 ± 14.6	4.7 ± 1.4	19.1 ± 20.3	4.8 ± 1.5
Range		1.2–41.3	1.2–6.1	3.3–37.2	1.9–7.0

[a]: Calculated on recorded stem number in the stand; [b]: Calculated on 1000 stems ha^{-1}.

4. Discussion

The first generation of poplar plantations in Sweden are about 20 years old and most of them are due to be cut in the near future. Their owners are interested in identifying options for the future management of the plantations following cutting. As such, information on the sprouting ability of poplar stumps, the number of living stumps and the dry mass production per stump and hectare are important factors in determining the owners' optimal course of action. One option for the plantations' future management will be to encourage stump sprouting. The sprouts can be used for biomass production or, after removing most of the sprouts from each stump, for pulp wood production. In the future, sprout biomass could represent a valuable source of bioenergy and become an economically important component of poplar forestry operations.

When analyzing the results obtained in this work, it is important to note that we examined relatively old stumps (8–21 years) whereas previously published works on poplar sprouting have focused on seedlings cut at 1–3 years of age. Poplar sprouting is generally vigorous [27], but most of the published results in this area relate to young poplars (2–6 years). In most species, older stumps have lower numbers of dormant buds [14,28]. However it has also been reported that the abundance of bud clusters increases with stump age [28]. In this work, few visible buds were observed on the poplar stumps, and the sprouts that were observed appeared to have initially developed between the cambium and the bark. Many sprouts emerged in the upper part of the stump. However, many of these sprouts were unstable and fell after 1–2 vegetation periods. Sprouts emerging from the lower part of the stump were more stable.

In a study of an Eastern cottonwood stand harvested monthly during a year, the harvest between January and March yielded the greatest number of sprouts [8]. The lowest number of sprouts was found after harvest between April and August. Stumps cut during this period yielded the greatest sprout heights and diameters. In our study, the number of sprouts per living stump decreased as the length of time since cutting increased. Within one year of cutting, the mean number of sprouts per living stump was 18–37 with a range of 2 to 68. Conversely, trees that had been cut 7 years ago had only 3 (1–12) sprouts per living stump. The increasing sprout size and the larger leaf area increase the interior competition with suppressed and dying sprouts [29]. There are indications that sprout suppression might be clone specific. In a 6-year old coppice culture of 17 different clones the authors reported that the number of sprouts per stool was highly clone specific. Within a clone the number of sprouts after cutting was positively correlated with the stool size [29]. Table 8 presents the per-stump sprout numbers reported in previous studies on poplar coppicing. As shown by the table, most previous authors observed fewer sprouts on 1-year-old stumps than were seen in our study.

The power model fit the data well. In our study the biomass was expressed as depending on diameter of sprouts at 0.1 m above ground level. An application of biomass *vs.* sprout age is another way but in practice you may have to know the age of the sprouts. Diameter of the sprouts is easy to measure and in practice a convenient way to estimate the sprout biomass.

The timing of harvesting is important in determining a stump's sprouting ability [16]. All of the stands examined in this work had been cut between November and March. A study conducted in Wisconsin on 1-year-old sprouts of the clone NE-299 (*P. nigra* var. *betulifolia* × *P. trichocarpa*) indicated that stump survival rates were 65%, 9% and 5% for poplars cut in June, July and August, respectively, compared to 92% and 93% for trees harvested in September-May, respectively [9]. The percentage of surviving stumps observed in this work ranged from 57% to 100%. The percentages for 1-year-old sprouts were 79–100% while that for the oldest 7-year-old sprouts was 70%. Few or none of the sprouts had been damaged by wild animals, pathogens or insects. As shown in Table 8, previous studies on young poplar stumps have produced results consistent with those observed in this work. It has previously been shown that extensive coppice management (planting seedlings directly on the bare soil without herbicides or fertilizers) yielded lower stump survival rates than intensive management involving adding fertilizers and other beneficial chemicals [37]. In a study by Laureysens *et al.* [29], the number of sprouts per living stump varied depending on the clone used, with *Populus tricoharpa* and *P. trichocarpa* × *P. deltoides* clones giving the greatest number of sprouts.

Many previous studies have demonstrated that when using common short rotations (≤3 years), coppiced stands are more productive than their planted counterparts [27,38–40]. Sprouts grow more rapidly than seedlings because they can use the stump's pre-existing root system. They also rapidly develop a high leaf area index (LAI) [41]. Herve and Ceulemans [27] studied coppiced and planted stands of five different poplar clones in Belgium and France, and observed that the height and diameter of 3-year-old sprouts were 1.77–3.49 m. and 17.8–30.0 mm, respectively, whereas those of 3-year-old seedlings were 1.21–1.94 m. and 10.5–16.8 mm, respectively. After three years the volume index (d^2h) dm^3 for the coppiced stands was lower than for the planted stands [27]. The diameters and heights of 3-, 4-, 5- and 7-year-old sprouts examined in our study were compared to the corresponding values for planted poplar seedlings of the same age. Most of the planted poplars used in this comparison were grown in Sweden and were of different clones to the stumps examined in this work; however, the 3 year old planted seedlings were of the same clone and were grown in the Czech Republic. As shown in Table 9, the older seedlings (7 years) were taller than the sprouts.

Table 8. Reported sprout characteristics for poplar (*Populus* sp.).

Reference	Sprout age years	No. sprouts (stump^{-1})	Living stumps (%)	Total production (tons ha^{-1})	Sprout Height (m)	Sprout Diam. (mm)	Remarks
30	3	-	-	0.61–4.40	2.8–4.1	20–43 [1]	*Populus nigra* spp. *nigra* Czech Republic.
	3	-	-	3.18–4.23	3.4–4,7	36–45 [1]	NE-42 (*P. maximowisczii* × *P. trichocarpa*).
31	4	7.5–16.8	50–87	6.6–7.9	-	-	*Populus nigra* spp. *nigra* Czech Republic
	4	9.3	68	9.4–9.8	-	-	NE-42 (*P. maximowisczii* × *P. trichocarpa*).
13	3	1	85–90	2.0–3.9	1.5	20 [2]	"Beaupré" (*P. trichocarpa* × *P. deltoides* France.
32	1	-	-	2.9–8.3	-	-	Belgium.
33	4	8.0	-	26	6.6	44 [3]	*P. trichocarpa* Mount Vernon, Virginia.
	8	1.4	-	52	10.9	69 [3]	*P. trichocarpa* Mount Vernon, Virginia.
29	1	3–7	3	-	-	-	17 clones. First coppicing. Belgium and France.
	4	8–19	7–65	6.4–43.2	-	20–68 [4]	Second coppicing after 4 years growth.
34	1	-	-	2.8	-	-	Balsam spire (*P. balsamifera* × *P. trichocarpa*)
	2	-	-	13.9	-	-	Scotland.
	3	-	-	33.6	-	-	-
	4	-	-	27.1	-	-	-
	6	-	-	55.9	-	-	-
10	1	8.3–20.1	-	-	1.0–1.3	8–10 [2]	"Tristis" (*P. tristis* × *P. balsamifera*) Wisconsin.
	2	6.0–14.9	-	-	1.6–2.4	10–17 [2]	-
	3	2.2–4.2	-	-	3.4–4.2	21–28 [2]	-
35	4	2.6–4.4	22–94	12–30	-	26 [2]	17 clones. First coppicing. Belgium.
9	1	3.4–7.5	92–93	-	1.5–2.3	5–9 [2]	NE-299 (*P. nigra* × *P. trichocarpa*) Wisconsin.
27	3	-	-	-	1.8–3.5	18–30 [2]	5 poplar clones. Belgium.
36	3	10	-	-	9.0	71 [3]	Pennsylvania.

[1]: Diameter at 50 cm above ground (D_{50}); [2]: Diameter at 10 cm above ground (D_{10}); [3]: Diameter at breast height (DBH); [4]: Diameter at 22 cm above ground (D_{22}).

Table 9. Diameters (mm) and heights (m) for 4–8 year-old dominant sprouts and plants.

Stand age, years	Diameter DBH, mm		Height, m	
	Sprout	Plant	Sprout	Plant
3	70	20–43 [1,2]	4.6	2.7–4.3 [1,2]
4	89	76	10.0	7.5
5	120	69	9.2	9.7
7	158	149	11.9	13.0–14.4

[1]: Clones of black poplars and NE-42 [30]; [2]: Diameter at 50 cm above ground level.

Dickmann *et al.* [39] studied the effects of coppicing on aboveground growth and other factors in two poplar clones—“Eugeni” (*Populus* × *euramericana* (Dode) Guinier) and “Tristis I” (*Populus tristis* Fisch × *Populus balsamifera* L.)—at Michigan State University’s Tree Research Center. The height of the 4-year-old poplar plants was 8–11 m. (“Eugene”) and 3–3.4 m. (“Tristis”). The trees were then cut and the sprouts’ heights were measured after one year, giving values of 2.6–3.8 m (“Eugene”) and 1.3–1.7 m (“Tristis”).

Power models are commonly used to estimate tree biomass from simple measurements of size. However the accumulation of biomass in different tree components changes over time [42]. Al Afas *et al.* [35] have investigated whether a single biomass equation (power model) could be used for several years’ rotation and several poplar clones. They found that a single power model could indeed be used to estimate biomass production over rotation periods. The total potential for dry mass production varied between sites. Some previous studies on biomass production were conducted on experimental scales using small plots. Differences in yields between small plots and “field” stands with poorer average sites have been discussed by Hansen [38]. Field conditions include areas with poor sites, depressions, knolls and drainages. The stands examined in this work were grown under field conditions without fertilizers, although it should be noted that they were growing on former farmland. The mean dry sprout mass production per living stump was 16.1 ± 14.0 (range: 3.3–37.2) kg; the average mass production for the ten sites examined was 17 ± 15 (1–41) tons ha^{-1}, with an MAI of 4.7 ± 1.4 (1.2–6.1) tons ha^{-1} year^{-1}. As shown by Table 8 previous authors observed yields of 3 to 50 tons ha^{-1} depending on sprout age (3–8 years). Following a study conducted in the Czech Republic, Benetka *et al.* [30] reported that 29 clones of *Populus nigra* L. ssp. n*igra*) produced 0.61–4.40 tons ha^{-1} after three years, while the control clone NE-42 (*Populus maximowiczii* Henry × *Populus trichocarpa* Torr. and Gray) produced 3.18–4.23 tons ha^{-1}. At lower soil pH values, NE-42 had the highest production.

The stems, branches, and leaves accounted for 61 ± 8 (43–75), 8 ± 3 (2–23) and 31 ± 8 (7–53)%, respectively, of the sprouts’ overall dry mass. In a study of 17 poplar clones growing in Belgium, the corresponding proportions were found to be 71–75, 12–14 and 13–16 respectively [41]. Proe *et al.* [34] reported that the proportion of the overall above ground dry mass that was attributable to leaves decreased year on year for the “Balsam spire” hybrid poplar (*P. balsamifera* var. Michauxii (Henry) × *P. trichocarpa* var. Hastata (Dode) Farwell): at the end of the first year of coppicing, leaves accounted for 41% of the total dry mass, which fell to 25, 16, 10 and finally 9% over the next four years. Pellis *et al.* [32] reported that leaves constituted 32–44% of the total dry mass in seventeen 1-year-old poplar clones in Belgium.

Basic density (g cm^{-3}) can be used to estimate dry weight if the volume is known. High densities indicate that would accounts for a large proportion of the tree or sprout's mass. In our study the mean basic density of the sampled sprouts was 0.323 ± 0.012 (0.200–0.467) g cm^{-3}. No reports dealing with basic density for poplar sprouts was found by us.

Projected Leaf Area (PLA) values are used in light interception studies and are useful indicators of biomass productivity in fast-growing trees [43,44]. Moreover, leaf area development and individual leaf size have been linked to productivity in *Populus*. In our study the mean observed PLA was 50 (13–143) cm^2 and the mean SLA was 85 ± 25 (36–200) cm^2 g^{-1} d. w. Our measurements of PLA and SLA mean values and ranges for poplar sprouts are compared with values for PLA of 47.4 ± 5.0 (range: 24–131) cm^2 and SLA of 85 (range: 36–200) cm^2 g^{-1} d. w. for single stem poplars ranging from 4–73 years [18] and for values measured in a study of seventeen different 1-year-old poplar clones aged, Pellis *et al.* [32] observed PLA values ranging from 45 to 174 cm^2 and SLA values of 160–211 cm^2 g^{-1} d. w. This comparison is made as there, as we have found, no observations on leaf characteristics have been reported.

5. Conclusions

The sprouting ability of older poplars planted on farmland was studied. Since the sprouts heights' were generally below the standard DBH value of 1.3 m, biomass equations were constructed based on sprout diameter 0.1 m above ground (D_{10}). To facilitate the field estimation of sprout biomass for sprouts taller than 1.3 m, it was determined that D_{10} values can be approximated as 1.35 × DBH. The proportion of living stumps in recently-felled stands of 8–21-year old poplars ranged from 57–100%, which is comparable to that observed in conventional coppicing with rotations of 3–6 years. The number of sprouts decreased with increasing sprout age: there were 2–68 sprouts per living stump for 1-year-old sprouts, but only 1–12 sprouts for 7-year-old sprouts. The mean dry sprout mass per stump was 16 kg (range: 3–37 kg), which corresponds to 17 tons ha^{-1} (range: 1–41 tons ha^{-1}). Based on our findings the age of sprouts before harvest of 1000 stems per hectare of 15–20-year old poplar might be 4–7 years. With stump mortality factored in, the biomass production from 7 year old sprouts was 37 tons ha^{-1} d.w. meaning that poplar sprout harvesting could be of substantial commercial value and that optimizing stump production could be an inexpensive and cost-effective management option for rapid biomass production.

Acknowledgements

Miss M. Johansson measured and cut stands and also performed the tree ring analyses in the laboratory. Linguistic revisions were made by Sees-Editing Ltd UK. All of the above are gratefully acknowledged. The Swedish Energy Agency provided financial support.

Conflict of Interest

The authors declare no conflict of interest.

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