Biomass production and survival rates of selected poplar clones grown under a short-rotation system on arable land

M. Trnka[1], M. Trnka[2], J. Fialová[2, 3], V. Koutecký[2, 3], M. Fajman[3], Z. Žalud[1], S. Hejduk[4]

[1]*Institute of Agrosystems and Bioclimatology, Mendel University of Agriculture and Forestry in Brno, Brno, Czech Republic*
[2]*ZEMSERVIS Experimental Station Domanínek Ltd., Domanínek, Czech Republic*
[3]*Institute of Automobile Transport and Principles of Technology, Mendel University of Agriculture and Forestry in Brno, Brno, Czech Republic*
[4]*Institute of Animal Nutrition and Forage Production, Mendel University of Agriculture and Forestry in Brno, Brno, Czech Republic*

ABSTRACT

Fast-growing woody plants that can be grown under short-rotation systems offer an alternative to food production on arable land, and serve as a potential source of renewable energy. In order to establish the feasibility of future large scale production under the conditions of the Czech-Moravian highland, a high density experimental field plantation including a range of available clones of *Populus* sp. and *Salix* sp. with the total area of 1.5 ha was established in early 2001 in Domanínek (Czech Republic, 49°32'N, 16°15'E and altitude 530 m). The clone experiment of *Populus* sp. covered 0.3 ha in the center of the plantation and included 13 clones in total, with hardwood cuttings of only 6 clones available in numbers allowing 4-replicate experiment. The plantation was established on agricultural land and the trees were planted in a double row design with a density of 10 000 trees/ha. The trial was weeded by mechanical methods, and no irrigation, fertilization, or herbicides were applied. The experiment site was harvested at the end of 2006. It was found that the biomass yields of the tested clones of *Populus* sp. were in the higher range of results from national and European studies in case of hybrid clones. The satisfactory survival rate in the first year, when mortality tends to be highest, was supported by relatively wet weather conditions after plantation establishment. At the end of the first rotation, the highest yields were obtained from clones J-105 and J-104 (*P. nigra* × *P. maximowiczii*) and P-494 (*P. maximowiczii* × *P. berolinensis*) with J-105 showing a mean annual increment of dry matter close to 14 t/ha. Additional experiments seem to suggest that well managed poplar plantation might produce even better values if higher survival rates can be achieved.

Keywords: *Populus* sp.; short rotation forestry; bioenergy; biomass; coppice

Fast growing woody plants suitable for growth under short-rotation systems for the production of biomass present an alternative method to food production on the arable land, especially in those regions where food production is less profitable due to climate and/or soil conditions. Short rotation forestry (SRF) has been investigated since the mid 1960s with research focused on growing willows in Sweden (e.g. Siren et al. 1987) and silage sycamore in North America (e.g. Mitchell et al. 1999) to produce fiber for the paper and pulp industry. In the 1970s following the oil crises, the emphasis switched to producing woody biomass for energy purposes using fast-growing broadleaved trees such as poplar, willow or aspen with close spacing up to 20 000 plants/ha and under an intensive management system that resembles more agricultural practice than forestry (Mitchell et al. 1999). Since

Supported by the Ministry of Education, Youth and Sports of the Czech Republic, Project No. 6215648905, and by the Bystřice nad Pernštejnem Town Council.

the 1980s, Europe has shown a renewed interest in the use and technical realization of renewable energy as a means of reducing CO_2-emission levels from fossil fuels into the atmosphere. Under the Kyoto Protocol, the European Union committed itself to an 8% reduction in annual green house gas emissions, compared to the reference year 1990. The advantage of SRF plantations as a source of renewable energy in some parts of Europe lies in their relatively high biomass yield potential, good combustion quality as solid fuels, ecological advantages, comparatively low production costs, and the fact that they offer an alternative use for land that is not utilized for agricultural production (Kauter et al. 2003, Updegraff et al. 2004). Despite this, the actual production areas in Europe remain very small, with the largest acreage of the SRF found in Scandinavian countries, UK, Italy, Belgium, Germany, and France. However, in some of these countries, stagnation of SRF has been observed recently (Helby et al. 2006). One of the main reasons of the low SRF acreage (given the support and press coverage) is that as an energy source, the wood from SRF has to and will have to compete with fossil fuels, with other sources of renewable energy (e.g. wind, geothermal or solar energy), and with other products of agriculture that may be utilized for energy production (e.g. bio-ethanol, rape-seed oil and RME, straw or bio-gas). Furthermore, in most conditions, SRF is inferior under the given economic and political conditions (e.g. Mitchell et al. 1999, Kauter et al. 2003). At the same time, a great hope placed on SRF as a renewable energy source during 1990s was somewhat diminished by unimpressive results at the farm level and by unsuitable agricultural policies on the national and EU level (Helby et al. 2006). However, a number of studies documented that by using optimal genotypes and management practices, yields could be optimized to profitable levels (e.g. Kauter et al. 2003, Laureysens et al. 2004). This suggests that SRF is a viable option for farmers in many regions, including central Europe.

The key parameter determining the economic sustainability of any SRF plantation is its biomass productivity, usually expressed in tons of dry matter per hectare per year (t/ha/year). The yield of poplar-based SRF given in the literature differs considerably and is affected not only by the genotype of the plant but also by weather conditions and management practices that influence survival, inter- and intra-species competition, and final vigor of the stand. While the reported maximum yield lies between 20–25 t/ha/year mean annual increment (MAI) (e.g. Scarascia-Mugnozza et al. 1997), other studies report MAI in the range of 1.5–6.0 t/ha/year (Benetka et al. 2002, Kauter et al. 2003, Gruenewald et al. 2007). These differences reflect mostly the type of the trial with the highest yields being derived from intensively managed, small experimental plots, while the lowest ones are found in marginal areas with low intensity (or no) weed management. Another problem that contributes to validity of extrapolating small scale experimental yields to field scale is, as it has been shown in the case of poplar clone Tritis as an example, that yields can vary at the same site from 25–30 t/ha/year in small plots and 10 t/ha/year for large scale experiments (Cannell 1988). Based on recently published data, the average harvestable yields of poplars from SRF in temperate regions of Europe and North America range between 10 and 15 t/ha/year (Hoffmann-Schielle et al. 1999, Kauter et al. 2003, Lewandowski et al. 2006, Van de Walle et al. 2007) and this yield level might be reasonably expected from well-managed plantations.

The most comprehensive overview of yield levels relevant for the Czech Republic might be found in Havlíčková et al. (2005) and Van de Walle et al. (2007) while experimental results for various regions of the Czech Republic were published by Lewandowski et al. (2006) and Benetka et al. (2007). More thorough and region-specific testing of SRF productive capacity is one of the key elements of viable SRF establishment (e.g. Laureysens et al. 2004, Van de Walle et al. 2007) and it is also the main motivation of the presented study. The partial objectives of this paper might be then summarized as follows:

(1) to quantify the above ground biomass production of selected poplar clones in a short rotation culture after a 6-year rotation;
(2) to assess the survival rates and annual biomass increments during the 6-year cycle;
(3) to study differences in the productivity and survival rates between tested clones.

MATERIAL AND METHODS

Experimental plantations and management regimes

In April 2001, a high density experimental field plantation for verification of performance of selected clones of *Populus* sp. and *Salix* sp. with the total area of 1.5 ha was established in Domanínek (Czech Republic, 49°32'N, 16°15'E and altitude

530 m) with clone experiment (CE) of *Populus* sp. occupying 0.3 ha near the center of the plantation. The plantation was established on agricultural land previously seeded predominantly with cereals and potatoes. During the last year of cropping, an oat-pea mixture was used as a pre-crop to prepare the field for plantation establishment. Soil sampling took place prior to planting in August 2001. Soil conditions at the CE location are representative to the wider region with deep luvic cambisol influenced by gleyic processes and with limited amount of stones in the profile. Table 1 contains basic soil and climate characteristics of the experimental site. The site itself is situated on a mild slope of 3° with an eastern aspect within a wire fence against unwanted disturbances by herbivores. The area is generally subject to cool and relatively wet temperate climate typical for this part of Central Europe with mingling of continental and maritime influences (Table 1). The site climate is suitable for SRF based on *Populus* sp. clones according to Havlíčková et al. (2006) as the area belongs to the climatic region no. 7. Weather parameters were obtained from the meteorological station Bystřice nad Pernštejnem (Czech Republic, 49°32'N, 16°16'E and altitude 560 m) of the Czech Hydrometeorological Institute, which is less than 1000 m from the experimental plots. The 6-year rotation period (2001–2006) was characterized by favorable first two years but with higher incidence of droughts in the later years (Figure 1). As might be seen in Table 1 temperatures during summer, winter and the entire vegetation period were higher than during 1961–1990 reference period with the precipitation close to the normal level.

Hardwood cuttings were planted in a double row design with inter-row distances of 2.6 m and spacing of 0.7 m within rows accommodating density of 10 000 trees/ha. In total, the trial included 13 clones. However, for 7 of them the available

Table 1. Selected climate and soil characteristics of the experimental site

Climate characteristics					
Parameter	Units	January–December	April–September	June–August	December–February
Mean air temperature: 1961–1990	°C	6.6	12.8	15.5	–2.7
Mean air temperature: 2001–2006	°C	7.3	13.8	16.9	–2.3
Precipitation sum: 1961–1990	mm	580.6	359.6	208.3	113.0
Precipitation sum: 2001–2006	mm	590.6	358.6	208.3	124.7
Soil characteristics					
Component	Units	Depth (cm)			
		0–24	24–66	66–94	94–130+
Sand	wt %	34.2	27.6	42.7	67.1
Silt	wt %	50.0	46.1	38.7	19.6
Clay	wt %	15.8	26.3	18.6	13.3
Bulk density	g/cm^3	1.55	1.64	1.59	1.64
Organic matter	wt %	2.65	0.28	0.14	0.14
Total nitrogen	wt %	0.16	< 0.05	< 0.05	< 0.05
pH (KCl)		5.9	5.4	4.0	3.4
Available P	mg/kg	148	1.3	0.9	24
Available K	mg/kg	151	91	62	76
Available Mg	mg/kg	143	230	278	291
Available Ca	mg/kg	1230	1353	748	652

Fraction of sand (0.05–2 mm), silt (0.05–0.002 mm), clay (< 0.002 mm); organic matter and total nitrogen are expressed in terms of weight fraction (wt %). The concentration of available nutrients was determined by Mehlich III method

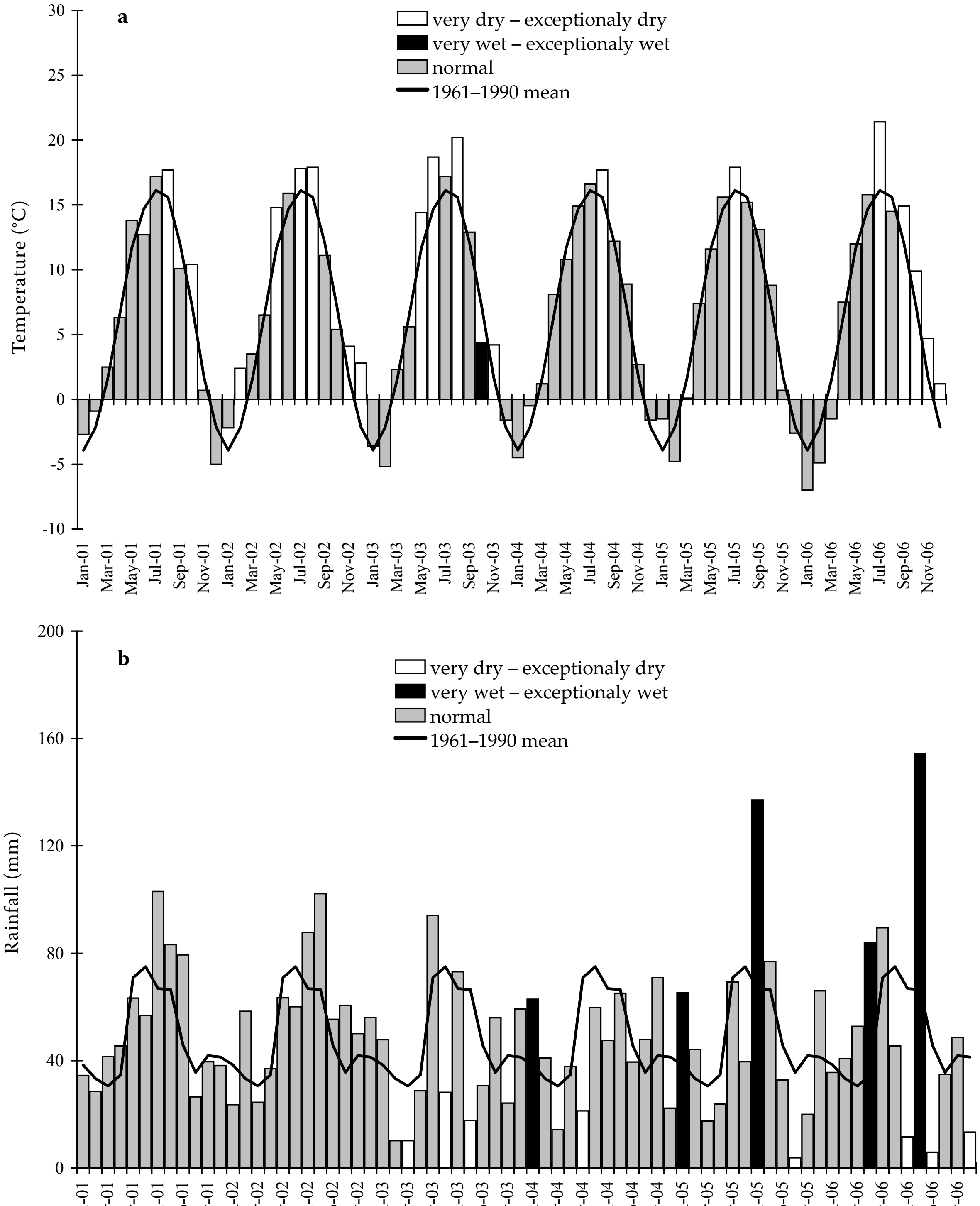

Figure 1. Dynamics of mean monthly temperatures (°C) and monthly precipitation sums (mm) during the experimental period (2001–2006) in comparison with the 1961–1990 period (visualized as a solid line). The thresholds of World Meteorological Organization for evaluation of the meteorological conditions were used (Kožnarová and Klabzuba 2002)

planting material was insufficient to allow a full-scale analysis. Still, a randomized block design assuming 13 clones × 4 replicates was adopted, with those variants for which planting material was not available being planted with the J-105 clone to avoid a border effect. The size of the plots and number of clones tested was unfortunately limited by the availability of the cuttings for individual clones at the time of the experiment initiation (i.e. 2001). Thus the presented study includes only results of six clones for which a fully representative trial could be established, i.e. monoclonal

Table 2. List of the clones and their parentage in the clone experiment (CE) and clone survival experiment (CSE)

Clone abbreviation[a]	Code of the clone[b]	Parentage	Group	Country of origin of the clone[c]	Number of individuals: CE	Number of individuals: CSE
J-104	P-J-104*049	*P. nigra* × *P. maximowiczii* Maxvier	N × B	Austria	4 × 40 (n = 160)	n = 2 574
J-105	P-J-105*050	*P. nigra* × *P. maximowiczii* Maxfünf		Austria	4 × 40 (n = 160)	n = 10 010
P-494	P-Oxford-494	*P. maximowiczii* × *P. berolinensis* Oxford		USA	4 × 40 (n = 160)	n = 858
P-524	P-gomel2-524	*P. balsamifera* × *P. tremula* cf. *balsamifera*	B × B	USSR	4 × 40 (n = 160)	n = 858
P-473	P-trikor-473	*P. trichocarpa* × *P. koreana* (cf. *P. trichocarpa* × *P. deltoides*)		Italy	4 × 40 (n = 160)	n = 2 574
P. nigra	0036-Hrušky[d]	*P. nigra*	N. aut.	Czech Republic	4 × 40 (n = 160)	–

[a]clone abbreviation used by the Ministry of Agriculture of the Czech Republic (Věstník MZe – 1/2004)
[b]code of the clone used by The Silva Tarouca Research Institute for Landscape and Ornamental Gardening
[c]Havlíčková et al. (2005)
[d]Jiránek J. (2007 – personal communication)

plots (n = 40) in 4 replicates (Table 2). The experiment was placed within a larger plantation and the entire trial design and row orientation (E-W) was aimed at minimizing the border effect and influence of eventual soil nonhomogenities within the experimental area. Prior to planting the area was leveled and cleared of larger stones. Ploughing followed by a rotor tiller were used in the 2000–2001 season as the final pre-planting preparation. All clones were planted as 25 cm long dormant, unrooted hardwood cuttings, after being soaked in water for 48 h prior to planting. Cuttings were planted manually to the depth of 22–23 cm leaving terminal buds above the soil surface. No replacement of individuals within the trial was done in order to simulate conditions of large-scale farming. Mechanical weeding was carried out on May 27 and June 31. The inter-rows were tilled by rotor tiller on September 20. In order to allow for good plantation establishment under significant weed pressure the plantation was not coppiced after the first year allowing it to close canopy during the 2nd year. During 2002–2003 the weed growth in inter-rows was managed by cutting combined with mulching 3-times a year. No irrigation, fertilization and herbicide treatments were applied during the experiment.

In April 2001 another experimental plantation (3.5 ha in total) with a 7-year rotation cycle was established using a smaller set of 5 *Populus* sp. and 3 *Salix* sp. clones for which the certified breeding material was available at the time. The field experiment plantation is less than 400 m away from the CE with similar soil conditions and the same exposition. The total area and number of individuals of each clone is listed in Table 2. The same methods of field preparation and weed control as in the case of the clone trial were used. The main purpose of the plantation is to serve as a model field (both in terms of size and composition) to the eventual future plantations in the region and it was used to evaluate survival rates of *Populus* sp. clones under field conditions taking advantage of a large number of individuals. Hereinafter, it is referred to as the clone survival experiment or CSE.

Biometric measurements

Between November 20 and December 5 2006 all individuals at each plot in CE were cut at the height of 20 cm above ground and then processed by a wood-chipping machine (Vandaele TV 160, Oostrozebeke, Belgium) with the exception of border plants. The total amount of wood harvested from each plot was weighed by a properly maintained and calibrated weighting machine (scale precision of ±1.0%). After the weighting, the total above-ground plot biomass of 8 samples (0.5 kg each) were taken at different spots in the pile and mixed together. The mixed sample was immediately air dried for 24 h at 80°C and then at 105°C until it reached a constant weight. Shoot diameter of each tree within the assessment part of the plot was determined prior to the harvest at the height of 20 cm above ground. At each trunk two perpendicular measurements were taken and the diameter was determined as the measurement average. Tree height was determined immediately after cutting each individual as the distance from the cut to the tip of the main trunk. Plant density at the CE trial was determined by counting the number of living trees on each plot at the end of the growing season. In the case of CSE, the number of dead (missing) individuals was assessed at the end of each season because of a high number of individuals in the experiment.

Statistical analysis

Data analyses were performed using the statistical package Unistat 5.7 (Unistat Ltd., London, UK). An analysis of variance (ANOVA) was used to test the significance of differences in biomass production, survival rates, diameter and height between clones (6) and parentages (3). A randomized complete block design was applied, with clone

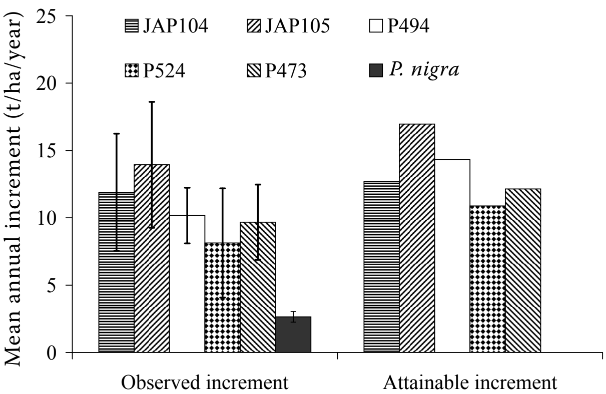

Figure 2. Left – Observed mean annual increments (MAI) in the clone experiment expressed as dry matter in tons per ha and year (t/ha/year) over 6-year rotation period for 6 tested clones. Standard deviation of the MAI is given. Right – Estimate of attainable MAI at the Domanínek site assuming the observed production level in the clone experiment (CE) and mortality rates observed in the clone survival experiments (CSE) – Figure 4

or parentage as a fixed factor and replicate as a random factor. Least squares means where means were pair-wise compared for clone and parentage were considered significant when the *P*-value of the ANOVA *t*-test was < 0.05. Data were tested for normality by Kolmogorov-Smirnov test using the significance definition of Lilliefors (1967), adopting the correction introduced by Dallal and Wilkinson (1986). Linear correlations between parameters were tested for significance using Spearman's rank correlation test, with correlation being considered significant at $P < 0.05$ level.

RESULTS AND DISCUSSION

Above ground biomass production

Differences among clones in their mean annual above ground biomass production were considerable (Figure 2, Table 3), with MAI ranging from 2.6 t/ha/year for *P. nigra* to 13.9 t/ha/year in the case of J-105. Three clones (J-104, J-105 and P-494) showed MAI values of more than 10 t/ha/year of dry matter with P-473 being very close to this level. The differences between the three most productive clones were not statistically significant. The J-105 showed significantly higher yields only compared to *P. nigra* and P-524 and there was no statistical difference between the two groups of hybrid clones according to parentage in terms of biomass production. On the other hand the tested autochthonous clone of *P. nigra* showed very poor performance with yields being less than 3 t/ha/year (Figure 2).

The obtained levels of MAI are comparable with the range of 4.4–11.12 t/ha/year reported for various production regions in the Czech Republic by Lewandowski et al. (2006). The highest yields according to this study are to be expected in slightly warm and wet climates of cereal and potato production regions (i.e. 11.1 and 9.1 t/ha respectively). On the other hand, the yields reported by Havlíčková et al. (2005) are slightly lower than those obtained in the experiment (Table 3). Benetka et al. (2007) carried out trials in similar climate conditions as those in Domanínek but with a lower planting density and on soils of lower quality. We report a significantly higher MAI 7.6–7.9 t/ha/year for autochthonous *P. nigra* clones and 9.4 t/ha/year for hybrid clone (*P. maximowiczii* × *P. trichocarpa*). The production levels found in our study are also in the higher range of the results found in other European studies (including Belgium, Germany,

Table 3. Biomass productivity expressed in terms of mean annual increment of dry matter (MAI) during 6-year rotation and survival rates of six clones tested in the clone experiment (CE)

Clone	Biomass (dry matter t/ha/year)					Survival rate[a]		
	mean ± SD	range[b]	*CV* (%)[b]	mean of other experiments[c]	estimated potential productivity[c]	mean ± SD	range	*CV* (%)[a]
J-104	11.9 ± 4.4	5.8–18.0	36.6			73.1 ± 11.2	57.5–85.0	15.4
J-105	13.9 ± 4.7	8.0–19.4	33.5	9.45	–	64.4 ± 15.5	45–87.5	24.2
P-494	10.2 ± 2.8	5.4–12.6	27.5	2.77	5.3–6.2	58.1 ± 17.1	45–87.5	29.4
P-524	8.1 ± 2.1	6.0–11.3	25.4	2.00	4.2–5.1	69.4 ± 10.5	57.5–85.0	15.2
P-473	9.7 ± 4.1	3.4–14.4	41.9	3.19	6.9–8.0	51.9 ± 7.8	45–65.0	15.0
P. nigra	2.6 ± 0.4	2.3–3.3	14.6			36.9 ± 21.5	12.5–65.0	58.2

[a]survival rate is given as a proportion of surviving individual at harvest (December 2006) compared to the number of planted individuals
[b]the range and the coefficient of variation (*CV*) among replicates are presented
[c]based on the values published by Havlíčková et al. (2005) – data are based on 1–13 individual experiments across the Czech Republic

Great Britain and Sweden) where observed yields are between 2.2 and 13.6 t/ha/year (Van de Walle et al. 2007). However, in this case most of the experiments used only a 4-year rotation cycle compared to the 6-year rotation in the Domanínek experiment. Several other studies (e.g. Ceulemans et al. 1996, Armstrong et al. 1999, Laureysens et al. 2004, Labrecque and Teodorescu 2005) reported higher yields in small plot experiments with some cases reporting over 18 t/ha/year. As Laureysens et al. (2004) or more recently Van de Walle et al. (2007) demonstrated that soil quality is one of the key factors determining the yield levels provided that climate conditions are suitable for poplar growth with highest yields being reached on loam or sandy-loam soils. Especially in the conditions of the Czech Republic a combination of optimum climate and soils with sufficient fertility (Lewandowski et al. 2006) are key for sustaining high biomass productivity and economic viability of poplar plantations providing an adequate level of plantation management.

Besides relatively high interclonal variation in biomass production, a high inter-replicate variation (quantified in terms of coefficient of variation) was observed for some clones (Table 3). When *P. nigra* is not taken into account, the lowest plot biomass production was obtained for P-473 (i.e. 3.4 t/ha/year). On the other hand, the highest plot yields were recorded for J-105 (19.4 t/ha) and J-104 (18.0 t/ha). Despite differences among plots, the statistical analysis using ANOVA (least square difference method) showed that there was no statistically significant difference among replicates and that the substantial part of the experiment variability could be explained by interclonal variability. The question of high inter-replicate variability is of great importance and was reported by many other studies (e.g. Venendaal et al. 1997, Laureysens et al. 2004, Van de Walle et al. 2007). It has been mostly explained by heterogeneity of the physical and chemical characteristics of the soil. However, the cited studies failed to establish convincing links between inter-replicate differences in soil conditions and yield variability. Based on the experience collected so far, the authors presume that a whole complex of factors (weather conditions during plantation establishment; variations in the vitality of individual cuttings, micro-scale competition for resources with weeds and probably also small scale soil heterogeneity) might be the root cause of this phenomenon but an additional experiment will be required to verify the hypothesis.

Stem diameter and height

The mean diameter of the main poplar trunk after 6 years showed a high variability (Figure 3a) reaching from 5.9 cm (*P. nigra*) up to 10.1 cm (P-473) with some individuals reaching diameters over 18 cm

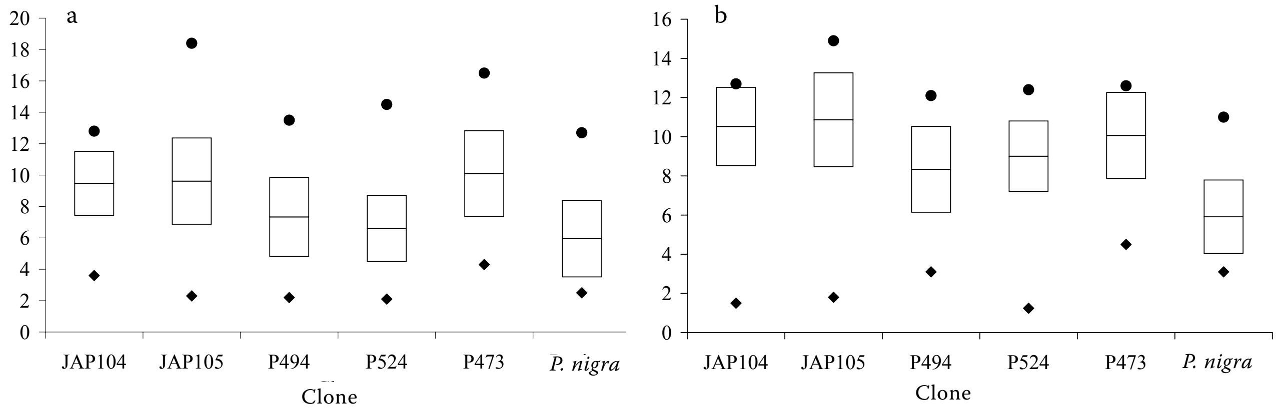

Figure 3. (a) Observed trunk diameter of 6 clones in the clone experiment (CE) in cm after 6 years (i.e. at harvest); (b) Observed trunk height at CE in m. White vertical bars depict mean ± standard deviation while points show maximum (black) and minimum (gray) diameter (height) of all surviving individuals in the experiment

just before harvest (in case of JAP 105). The *CV* of the diameter in the clone experiment was lowest in the case of J-104 ($CV = 21.5\%$) and highest in the case of *P. nigra*, which reached 40.9%. Based on the ANOVA analysis, the J-105 and P-473 clones had significantly greater diameters than *P. nigra* and P-524. However, there was no difference among clones based on parentage.

The height of the canopy seems to be a more stable parameter than the diameter with the *CV* ranging from 20.0% to 31.7% with five of the six clones being on average taller than 8 m (Figure 3b). Most of the J-105, J-104 and P-473 canopy was taller than 10 m with some individuals of J-105 reaching a height well above 14 m. The three listed clones were also found significantly taller than the autochthonous *P. nigra* clone.

Survival rates

The accumulated mortality during the whole CE duration ranged between 27% (in the case of JAP 104) and 63% (in the case of *P. nigra*) and this can explain over 57% of interclonal yield variability. Clones J-105, J-104 and P-473 showed the highest survival rates that were significantly greater compared to *P. nigra*. However, there were no significant differences in survival rates between hybrid clones or parentage groups. Obviously the

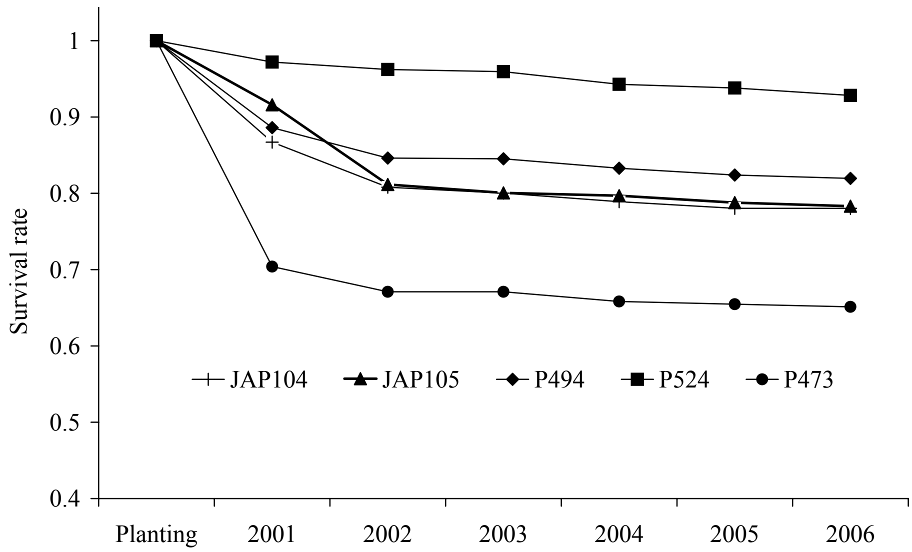

Figure 4. Survival rate of 5 clones tested in the clone survival experiment (CSE) assessed over all individuals of each clone in the trial (Table 2). The survival rate is expressed as the ratio of living poplar plants at the end of each season vs. planted number of cuttings

clones with low survival rates (i.e. high mortality) tend to produce less above ground biomass as resources freed by the dieback (e.g. light, water and nutrients) are utilized by competing weeds, and remaining poplar plants are not able to fully close a canopy that would control weed growth naturally. The data (Table 3) indicate high inter-clonal variability in survival rates in the CE and this is even more apparent when data from the CSE are analyzed (Figure 4). The CSE setup provides a more robust estimate of survival rate due to a much higher number of individuals in each replicate. The survival rates found in CSE are on average higher than in the CE with the overall survival rate ranging between 62% (for P-473) and 93% (for P-524). The three highest yielding clones in the clone experiment (i.e. J-105, J-104 and P-494) showed favorable survival rates between 78 and 82% also in the CSE plantation (Figure 4). The survival rate dynamics clearly demonstrates the importance of the first year for plantation establishment. It is obvious that the highest dieback takes place within the first 6 months after planting. Figure 4 also shows differences in the dynamics of survival rates in the case of P-524, P-473 and the remaining three clones (J-104, J-105 and P-494). It is clear that the survival rate as well as their dynamics should be one of the key parameters for clone selection and breeding.

The effect of seasonal weather conditions after plantation establishment on the survival of the clones seems to be marginal in both CE and CSE. Even relatively cold and prolonged winters (2002/2003 or 2005/2006), long-term period of below-average precipitation and above-average temperatures (e.g. 2003) or severe shortage of precipitation at the beginning of the growing season (e.g. 2004) did not lead to higher mortality in poplars. It is very different from the *Salix* sp. clones that, within the CE and CSE experiments, showed a sharper increase of dieback especially after the 2003 and 2004 seasons, probably as a result of multiple environmental stressors and phytopathological pressure. The production plantations of *Populus* sp. that were planted during seasons 2003 and 2004 in the Domanínek region (over 19 ha in total) suffered greatly from a lack of soil moisture during the vegetation season and had to be either replanted completely (5 ha) or showed survival rates as low as 40% due to the unfavorable course of the weather after planting. This illustrates the importance of climate factors especially in the early stages of plantation establishment.

The survival rates of *Populus* sp. clones in the study were the same or higher than those reported by Laureysens et al. (2003) or Van de Walle et al. (2007). However, they were lower than 92–99% reported by Ceulemans et al. (1996) or those found by Havlíčková et al. (2005). The survival rates vary not only among individual clones but also among replicates explaining a significant portion of MAI inter-replicate variability. Out of the already listed reasons for inter-replicate variability of biomass, the survival rates are highly influenced by the competition with weeds during the plantation establishment. It is known that some of the perennial weeds (e.g. *Cirsium arvense*) can lead to 80% mortality rates if the plots are left untreated (Kauter et al. 2003). The competition with weeds is likely to be higher on former arable land due to a large amount of weed seeds inherently present in the soil (e.g. Smutný and Křen 2002), and the higher ability of weeds to take advantage of available soil nutrients compared to cuttings during the early establishment stage (Kauter et al. 2003). Successful weed management during the first years is in fact the key to successful plantation establishment, fast growth and hence high biomass production.

Determinants of biomass production

For all 24 plots, an analysis was made of the correlation of total biomass with the cumulated survival rate at the end of 2006, with the mean trunk height at the plot and mean trunk diameter at 20 cm above ground measured at the end of the 2006 season. A positive relationship between biomass and survival rates was expected and confirmed by the Spearman's rank correlation test (R = 0.381). The total biomass was also highly correlated with diameter (R = 0.596) and especially with the height (R = 0.857), which was found to be by far the best predictor of biomass yield. More experimental results are however needed in order to develop a reliable clone specific allometric power equation between the diameter of stems (cm) and the total dry biomass at the end of the 6-year rotation similar to those proposed by Laureysens et al. (2004). For the present time a provisional allometric relationship was established between the survival rate, diameter and height, which is able to explain almost 80% of the biomass production at the site with mean bias of 11.0%.

Attainable biomass production

Lower survival rates at the clone trial are most likely a consequence of higher competition from weeds as the CE area was found under higher infestation pressure from competitive species (including *Cirsium arvense* L.) compared to the CSE despite the same intensity of weed management. If the level of productivity per plot achieved in the clone trial is combined with the survival rates of the CSE (Figure 4) a level of practically attainable yield could be estimated for five out of six tested clones, as *P. nigra* was not planted at CSE. In such a case a mean annual increment between 11 and 17 t/ha/year could be expected (Figure 2). The J-105, P-494 and J-104 were found to be the most productive clones at the site with 17.0, 14.3 and 12.7 t/ha/year, respectively. Theoretically, yields over 20 t/ha/year could be achieved for the best tested clones if we assume 100% survival rates and calculate this with the production level per individual obtained in the CE experiment. This is supported by the highest yielding replicate of J-105 (19.4 t/ha/year). However, given the relatively high mortality even in the well managed plantations (Figure 4) and the results of other studies (e.g. Armstrong et al. 1999, Laureysens et al. 2003, Vande Walle et al. 2007) it seems clear that the attainable yield levels for poplar plantations assuming a density of 10 000 individuals per hectare are not realistic. At least 10–40% mortality (depending on the clone, weather conditions in the season and particular site) has to be taken into account. Weed management and survival rate enhancement remain the key problems in SRF on the production level that prevent larger scale SRF adoption by many farmers (Helby et al. 2006).

Biomass yields for selected clones of *Populus* sp. included in this study were in the higher range of results from national and European studies on hybrid clones. The level of production at the experimental site in Domanínek was mainly caused by favorable climate conditions with sufficient precipitation, relatively fertile soil, efficient weed management after the plantation establishment, and a 6-year rotation schedule that is longer than in most other studies. The satisfactory survival rate in the first year, when the mortality tends to be highest, was supported by relatively wet weather conditions after plantation establishment. At the end of the first rotation the highest yields were obtained from clones J-105 and J-104 (*P. nigra* × *P. maximowiczii*) and P-494 (*P. maximowiczii* × *P. berolinensis*). The study also shows that a well-managed poplar plantation might produce even better results than observed in the clone experiment itself providing higher survival rates while maintaining the reported production level. Under such circumstances the poplar plantation of formerly arable lands are capable of producing sufficient amounts of dry matter per unit of area (up to 17 t/ha/year i.e. 102 t/ha per 6 years) to be a competitive alternative to other renewable sources of energy in the region, provided that the production level could be sustained through subsequent rotations.

To gain optimal profit from all functions of SRF, including soil water protection and provision of a temporary habitat, it is important that non-invasive species suitable for the site are chosen, and that sustainable methods of plantation management that prefer mechanical methods (e.g. mulching) above the use of herbicides are applied. In addition, multiclonal (multi-species) plantations might confer better protection against severe pathogen attacks than monoclonal sites even though no signs of elevated risks were observed at the location. Optimization of the production in terms of its sustainability and assessment of auxiliary ecosystem services provided by SRF plantation will be the main aims of the ongoing research program at the experimental site.

Acknowledgements

The authors sincerely thank Mr. Jan Weger, M.Sc. (The Silva Tarouca Research Institute for Landscape and Ornamental Gardening in Průhonice), and Ing. Jiří Jiránek (formerly Czech Ministry of Environment) for their support during the early phase of the experiments.

REFERENCES

Armstrong A., Johns C., Tubby I. (1999): Effects of spacing and cutting cycle on the yield of poplar grown as an energy crop. Biomass Bioenerg., *17*: 305–314.

Benetka V., Bartáková I., Mottl J. (2002): Productivity of *Populus nigra* L. under short-rotation culture in marginal areas. Biomass Bioenerg., *23*: 327–336.

Benetka V., Vrátný F., Šálková I. (2007): Comparison of the productivity of *Populus nigra* L. with an interspecific hybrid in a short rotation coppice in marginal areas. Biomass Bioenerg., *31*: 267–274.

Cannell M.G.R. (1988): The scientific background. In: Hummel F.C., Palz W., Grassi G. (eds.): Biomass Forestry in Europe: A Strategy for Future (CEC – 3rd EC Biomass Development Programme: Energy from Biomass). Elsevier, London: 31–88.

Ceulemans R., McDonald A.J.S., Pereira J.S. (1996): A comparison among eucalypt, poplar and willow characteristics with particular reference to a coppice growth-modelling approach. Biomass Bioenerg., *11*: 215–231.

Dallal G.E., Wilkinson L. (1986): An analytic approximation to the distribution of Lilliefors' test statistic for normality. Am. Stat., *40*: 294–296.

Gruenewald H., Brandt B.K.V., Schneider B.U., Bens O., Kendzia G., Hüttl R.F. (2007): Agroforestry systems for the production of woody biomass for energy transformation purposes. Ecol. Eng., *29*: 319–328.

Havlíčková K., Knápek J., Vašíček J., Weger J. (2005): Biomass as a renewable source of energy. Acta Pruhoniciana, *79*: 1–67. (In Czech)

Havlíčková K., Weger J., Havlíčková B., Vrátný F., Táborská M., Knápek J., Vašíček J., Součková H., Gallo P., Hejda J., Kajan M. (2006): Methodology for analysis of biomass potential as renewable source of energy. Acta Pruhoniciana, *83*: 1–96.

Helby P., Rosenquist H., Roos A. (2006): Retreat from *Salix* – Swedish experience with energy crops in the 1990s. Biomass Bioenerg., *30*: 422–427.

Hoffmann-Schielle C., Jug A., Makeschin F., Rehfuess K.E. (1999): Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany, I., Site-growth relationships. For. Ecol. Manage., *121*: 41–55.

Kauter D., Lewandowski I., Claupein W. (2003): Quantity and quality of harvestable biomass from *Populus* short rotation coppice for solid fuel use – a review of the physiological basis and management influences. Biomass Bioenerg., *24*: 411–427.

Kožnarová V., Klabzuba J. (2002): Recommendation of World Meteorological Organization to describing meteorological or climatological conditions. Plant Prod., *48*: 190–192. (In Czech)

Labrecque M., Teodorescu T.I. (2005): Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern Quebec (Canada). Biomass Bioenerg., *29*: 1–9.

Laureysens I., Bogaert J., Blust R., Ceulemans R. (2004): Biomass production of 17 poplar clones in a short-rotation coppice culture on waste disposal site and its relation to soil characteristics. For. Ecol. Manage., *187*: 295–309.

Laureysens I., Deraedt W., Indeherbege T., Ceulemans R. (2003): Population dynamics in a 6-year old coppice culture of poplar. I. Clonal differences in stool mortality, shoot dynamics and shoot diameter distribution in relation to biomass production. Biomass Bioenerg., *24*: 81–95.

Lewandowski I., Weger J., Van Hooijdonk A., Havlíčková A., Van Dam J., Faaij A. (2006): The potential biomass for energy production in the Czech Republic. Biomass Bioenerg., *30*: 405–421.

Lilliefors H.W. (1967): On the Kolmogorov-Smirnov tests for normality with mean and variance unknown. J. Am. Stat. Assoc., *62*: 399–402.

Mitchell C.P., Stevens E.A., Watters M.P. (1999): Short-rotation forestry – operations, productivity and costs based on experience gained in the UK. For. Ecol. Manage., *121*: 123–136.

Scarascia-Mugnozza G.E., Ceulemans R., Heilman P.E., Isebrands J.G., Stetler R.F., Hinckley T.M. (1997): Production physiology and morphology of *Populus* species and their hybrids grown under short rotation. II. Biomass components and harvest index of hybrid and parental species clones. Can. J. Forest Res., *27*: 285–294.

Siren G., Sennerby-Forsse L., Ledin S. (1987): Energy plantations – short rotation forestry. In: Hall D.O., Overend R. (eds.): Biomass – Regenerable Energy. John Wiley and Sons, Chichester: 199–143.

Smutný V., Křen J. (2002): Improvement of an elutriation method for estimation of weed seedbank in the soil. Plant Prod., *48*: 271–278.

Updegraff K., Baughman M.J., Taff S.J. (2004): Environmental benefits of cropland conversion to hybrid poplar: economic and policy consideration. Biomass Bioenerg., *27*: 411–428.

Van de Walle I., Van Camp N., Van de Casteele L., Verheyen K., Lemeur R. (2007): Short-rotation forestry of birch, maple, poplar and willow in Flanders (Belgium)

Corresponding author:

Ing. Mgr. Miroslav Trnka, Ph.D., Mendelova zemědělská a lesnická univerzita v Brně, Ústav agrosystémů a bioklimatologie, Zemědělská 1, 613 00 Brno, Česká republika
phone: + 420 545 133 080, e-mail: mirek_trnka@yahoo.com