Available online at www.sciencedirect.com
ScienceDirect
Biomass and Bioenergy 31 (2007) 367–374
BIOMASS & BIOENERGY
www.elsevier.com/locate/biombioe

Comparison of the productivity of *Populus nigra* L. with an interspecific hybrid in a short rotation coppice in marginal areas

Vojtěch Benetka*, Filip Vrátný, Ivana Šálková

Silva Tarouca Research Institute for Landscape and Ornamental Gardening Průhonice, CZ – 25243 Průhonice, Czech Republic

Received 9 August 2005; received in revised form 18 January 2007; accepted 22 January 2007
Available online 6 March 2007

Abstract

Populus nigra as an autochthonous European woody species is irreplaceable in regions where it is not legal to plant allochthonous species. Twelve clones of *P. nigra* ssp. *nigra* and one clone NE-42 (*Populus maximowiczii* × *Populus trichocarpa*) were tested in two localities at altitudes of 515–600 m with annual temperatures 5.7–6.8 °C. Different cultural practices and nutrition were used in these localities. Rooted plants were set out (2222 plants ha^{-1}). The second harvest was carried out after 4 years in a 7-year crop. The yield of the best clones of *P. nigra* (7.6–7.9 t ha^{-1} yr^{-1}) approached the yield of hybrid clone (9.4 t ha^{-1} yr^{-1}) in a fertilised locality, with pH = 6.7 and lower rainfall amounts in the growing season. In a locality with pH = 5, without fertilisation and with high groundwater level the yield of clones of *P. nigra* was 4.6–2.2 t ha^{-1} yr^{-1}, in clone NE-42 it was 9.8 t ha^{-1} yr^{-1}. The most productive clones of *P. nigra* had a significantly higher number of shoots (16.8–14.2) than the clone NE-42 (9.3) and the mortality of their shoots was lower (14–31.4%) than in NE-42 (32.1%). Shoots 20–53 mm in diameter accounted for 50% of the volume index of shoots in almost 70% of *P. nigra* clones. In high-yielding clones of *P. nigra* the dry weight of lateral shoots in total weight ranged between 66% and 75% while in NE-42 it was 55%. Resistance to *Melampsora larici-populina* Kleb. was higher in the interspecific hybrid but the best clone of *P. nigra* had a similar level of resistance.

Keywords: Biomass production; Short-rotation coppice; Number of shoots; Autochthonous species; *P. nigra* ssp. *nigra*

1. Introduction

The species *Populus nigra* belongs to European autochthonous woody plants. On the contrary, generally grown poplar clones are interspecific hybrids. The species mainly used for interspecific hybridisation are the European species *Populus nigra* L., American *Populus deltoides* Marsh, *Populus trichocarpa* Torr. et Gray and Asian species *Populus maximowiczii* Henry. *P. nigra* is one of the parental components in about 60% of clones originating from interspecific hybridisation but it itself is not likely used in short-rotation coppices (SRC) even though there exist about 40 cultivars of this species [1]. Only exceptionally is it included in comparative trials within the genus *Populus* [2].

As an autochthonous woody plant, black poplar is irreplaceable in regions where it is not legal to plant allochthonous species (e.g. national parks). There are 190 000 ha of agricultural land in these regions in the CR. They are mostly situated at higher altitudes and are characterised by more unfavourable climatic and soil conditions; this is also why the bulk of these lands has been released from agriculture. Besides, it is required to plant an autochthonous species along the periphery of plantations with allochthonous species for which the black poplar is a suitable species again.

Therefore, there arises a question how suitable *P. nigra* is to be grown in short rotation forests and what its yield potential is in comparison with interspecific hybrid clones. Similarly like in many other species it is typical of a number of interspecific poplar hybrids that their productivity is higher than in parental species [3,4]. But some papers also reported good results of clones coming from a pure species [5,6].

*Corresponding author. Tel.: +420 296 528 253; fax: +420 267 750 440.
E-mail address: benetka@vukoz.cz (V. Benetka).

0961-9534/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biombioe.2007.01.005

This is the reason why a trial to test the productivity of the species *P. nigra* in a short rotation plantation was established [7].

Besides the final trait, biomass yield, studies aimed at the growing of poplars for a short rotation plantation examine these traits: plant height, shoot diameter, number of shoots and their relation to biomass yield. High heritability of these traits [8] justifies the use of these traits for selection of suitable genotypes. It is to note that shoot diameter may be of higher importance than plant height [9]. In addition to these traits, leaf characteristics such as number of leaves per unit basal area, mean individual leaf area and maximum individual leaf area were studied and a correlation was found out between these traits and production of aboveground woody biomass [6].

Biomass yield per area is significantly influenced by the number of plants per area [10–14]. Most authors report an optimum density of 10 000 plants per ha.

The rust *Melampsora larici-populina* Kleb. is considered as an important external determinant of biomass production that may potentially cause plant mortality [6].

The objective of this paper is to evaluate the yield potential of black poplar in the second rotation and to examine the contribution of yield traits to the final trait biomass yield in relation to the origin of clones and to the fertility of growing sites.

2. Material and method

2.1. Locality, soil and climatic conditions

A trial was established in 1997 in two localities typical of areas where black poplar will be grown. The trial was established at two sites with different level of cultivation, different soil quality and weather conditions [7]. The characteristics of the two localities are (Table 1):

Smilkov (SM): Situated in a moderately warm and humid climatic region. The plot is arable land with relatively high humus content and nutrient supply, weakly acid soil reaction ($pH/CaCl_2 = 6.75$), and the soil type is Cambisol.

Bystřice (BY): Situated in a moderately cold, humid climatic region. Groundwater level is at about 30–50 cm. Water is drained to a near creek. The soil type is Histosol. Soil reaction is strongly acid ($pH/CaCl_2 = 4.95$). The plot has been set aside for about 50 years.

Precipitation was measured in the growing season (months IV–IX) in SM locality; the other data were taken from the most easily accessible meteorological stations.

2.2. Materials

Twelve clones of *P. nigra* were included in a field trial and one hybrid clone NE-42 (interspecific hybrid *P. maximowiczii* × *P. trichocarpa*) was used as a control (Table 2).

Table 1
Description of the study sites

Study site	Latitude N	Longitude N	Altitude (m a.s.l.)
Smilkov (SM)	49°36′	14°36′	515
Bystřice (BY)	49°21′	12°48′	551

Temperature (°C)

Study site	Mean year	Mean IV–IX	Mean IV–IX			
	1961–2000		2001	2002	2003	2004
Smilkov (SM)	7.7	13.9	13.4	14.7	15.7	13.7
Bystřice (BY)	8.0	14.0	14.1	14.8	16.1	9.4

Precipitation (mm)

Study site	Year total	Total IV–IX	Total IV–IX			
	1901–1950		2001	2002	2003	2004
Smilkov (SM)	655	393	501	548	265	368,5
Bystřice (BY)	755	448	—	—	—	—

Table 2
List of clones and their origin

Clone	Origin of clones—geographic data	
102	Central Bohemia	5020N 1429E
107	Southern Moravia	4848N 1657E
110	Southern Moravia	4848N 1657E
202	Central Moravia	4912N 1634E
204	Northern Slovakia	4905N 1936E
205	Northern Moravia	4938N 1822E
206	Southern Moravia	4848N 1657E
209	Southern Moravia	4848N 1657E
210	Southern Moravia	4848N 1657E
301	Southern Moravia	4846N 1658E
302	Southern Moravia	4848N 1657E
311	Southern Moravia	4848N 1657E

P. nigra clones are the progeny of individuals from local subpopulations from different localities of the CR characterised by different climatic conditions. Selection was made from a set of about 200 individuals (plus trees).

Planting stock was produced from woody cuttings 20 cm in length and about 5–6 mm in diameter.

2.3. Organisation and treatment

A compensation foregoing crop was planted at SM before the trial was established while at BY shrubbery was removed only without any other preparation.

The trial was designed as randomised blocks with four replications at each site, at SM five plants per replication, at BY four plants per replication, plant spacing 1.5 × 3 m. Both plots were fenced to protect them from damage by game.

The experimental planting stock, i.e. 1-year plants produced from cuttings in the previous year, was set out in spring 1997. A single irrigation dose was applied after planting at SM. All plants were trimmed at a height of 0.4 m after planting. At SM herbicides were applied in spring and mechanical weed control was carried out between rows twice a summer. Weeds at BY were mown only. The plantation was fertilised with a dose of 50 kg N; 50 kg P; 50 kg K ha^{-1} at SM in the third year in spring 2000. The same application rates were used at SM after harvest in spring 2001.

In February 2001, the 4-year plants were cut by hand at a height of about 10 cm for the first time. The second harvest was in March 2005.

2.4. Measurements

Every year at the end of the growing season plant height (H) and diameter of leading shoot at a height of 50 cm (D_{50}) was measured. Number of shoots was determined before the first and the second harvest. At SM diameters of all shoots were measured before harvest. In March 2005, all plants were cut 10 cm above the previous cut and fresh biomass was weighed in the best clones of *P. nigra* and in control clone and dry matter was calculated. To determine dry matter, samples were taken from the leading shoot and from lateral shoots separately. Samples were dried to a constant weight at 105 °C.

The degree of infection with the leaf rust *Melampsora larici-populina* Kleb. was evaluated using a point scale (0–5): 0—leaves absolutely free of rust infection symptoms; 1—small patches covered with rust sori on half the leaves; 2—small patches covered with rust sori on a majority of the leaves; 3—large patches or complete coverage with rust on all leaves; 4—whole leaves covered with rust, incipient leaf necrosis; 5—all leaves necrotised or shed.

Volume index $VI = D_{50}^2 H$ was calculated from the measured shoot diameter at a height of 50 cm (D_{50}) and total shoot height (H). Increments of plant height and shoot diameter were determined at the end of September. The sum of volume indexes of all shoots 20 mm and more in diameter for the studied clones ($SVI = \Sigma D_{50}^2 H$) was determined. The height of shoots was derived from the diameter of a given shoot. This procedure was based on a highly significant correlation between the diameter and the height of shoots.

The data were processed by one-way analysis of variance (ANOVA) and multiple range test (multifactor ANOVA) of homogeneous groups using the programme Statgraphics Plus for Windows 1.4. (1994–1995 by Statistical Graphics Corporation).

To determine the correlation between yield traits and biomass yield Spearman rank correlation test was used.

The terms "significant" and "highly significant" refer to $\alpha < 0.05$ and $\alpha < 0.01$, respectively.

Table 3
Yield of biomass dry matter from the second harvest, at a density of 2222 plants ha^{-1}

Clone	SM		Clone	BY	
	$t\,ha^{-1}\,yr^{-1}$	Homogenous groups		$t\,ha^{-1}\,yr^{-1}$	Homogenous groups
302	6.6	x	107	2.2	x
107	6.7	x	210	2.2	x
202	6.7	x	206	2.7	x
311	7.2	x x	301	3.4	x
210	7.3	x x	113	3.8	x
206	7.6	x x	309	4.3	x
301	7.9	x x	202	4.6	x
NE-42	9.4	x	NE-42	9.8	x

3. Results

3.1. Yield of biomass dry matter at second harvest (Table 3)

The results of the second harvest were multiplied up to give 2222 plants per ha. In both localities biomass production was higher in the hybrid clone NE-42 than the black poplar clones. In hybrid clone in the locality with more favourable conditions (SM) biomass yield was 9.4 $t\,ha^{-1}\,yr^{-1}$ while the yields of the best black poplar clones (301; 206) were not significantly lower (7.9 and 7.6 $t\,ha^{-1}\,yr^{-1}$). The yield of the best black poplar clones at BY was about a half of that of clone NE-42. It is to note that clone NE-42 had a higher dry matter yield at BY than at SM.

Only best clones of black poplar are reported.

3.2. Plant height; leading shoot diameter (Table 4)

Plants of clone NE-42 were not significantly higher than plants of the best clones of black poplar at SM (107, 301, 204, 311) and significantly higher than plants of black poplar at BY. Diameters of the black poplars were significantly lower than NE-42 at both sites.

3.3. Number of shoots

The number of shoots (Table 5) is a trait in which black poplar clones generally reach higher performance than hybrid clone. Before the second harvest the best clone at SM (206) had a significantly higher number of shoots 20 mm and more in diameter than the clone NE-42. In less favourable locality BY the number of shoots in all clones amounts to about 50% compared to SM locality. But even in this locality some black poplar clones have a higher number of shoots than NE-42.

We examined changes in the number of shoots in the period between first and second harvest. The average number of shoots formed before the first harvest was from 3 to 4.8 [7]. The number of shoots after the first harvest

Table 4
Volume index (VI), leading shoot diameter (*D*) and plant height (*H*) in clones planted at SM and BY

Clone	SM						BY					
	VI (dm^3)		*D* (mm)		*H* (cm)		VI (dm^3)		*D* (mm)		*H* (cm)	
102	31.2	x	68	x	666	x	12.7	x	50	x	509	x
107	41.6	x	75	ns	744	ns	23.5	x	61	x	641	x
110	27.4	x	63	x	687	x	9.3	x	44	x	484	x
202	27.7	x	65	x	658	x	22.9	x	61	x	610	x
204	33.6	x	68	x	721	ns	18.4	x	54	x	620	x
205	31.2	x	68	x	666	x	12.8	x	50	x	509	x
206	22.1	x	59	x	641	x	12.1	x	48	x	529	x
209	31.2	x	68	x	669	x	10.3	x	47	x	462	x
210	32.5	x	68	x	695	x	12.7	x	48	x	554	x
301	35.3	x	68	x	754	ns	18.7	x	56	x	602	x
302	29.9	x	67	x	659	x	18.3	x	55	x	597	x
311	31.8	x	67	x	710	ns	23.9	x	59	x	691	x
NE-42	58.4	—	86	—	791	—	65.0	—	88	—	830	—

Significance of differences relative to NE-42.

Table 5
Number of shoots after the first harvest (2001) and before the second harvest (2004) and the rate of their mortality

Clone	SM					BY				
	2001		2004		% mortality	2001		2004		% mortality
102	14.3	ns	10.1	ns	29.4	4.6	ns	4.7	ns	0.0
107	18.5	ns	10.8	ns	41.6	2.6	ns	2.9	ns	0.0
110	22.5	x	13.4	ns	40.4	6.8	ns	7.0	ns	0.0
202	19.7	ns	12.8	ns	35.0	10.0	x	10.0	x	0.0
204	13.7	ns	10.5	ns	23.6	7.6	ns	6.8	ns	10.5
205	12.7	ns	11.0	ns	13.4	5.4	ns	5.5	ns	0.0
206	24.5	x	16.8	x	31.4	7.1	ns	7.0	ns	1.4
209	19.5	ns	12.0	ns	38.5	6.7	ns	5.8	ns	13.4
210	17.0	ns	12.4	ns	27.1	7.9	ns	6.3	ns	20.2
301	16.5	ns	14.2	ns	14.0	6.3	ns	6.7	ns	0.0
302	15.0	ns	7.5	ns	50.0	1.9	ns	1.6	ns	15.8
311	19.0	ns	13.4	ns	29.5	4.5	ns	4.3	ns	2.9
NE-42	13.7	—	9.3	—	32.1	6.3	—	4.7	—	25.4

Significance of differences relative to NE-42.

(2001) increased markedly and it was higher in most clones of black poplar compared to clone NE-42; this difference was significantly higher in clones 206 and 110 at SM and in 202 at BY. The increment of the number of shoots in 2004 can be explained by faster growth of thin shoots or by inaccurate estimation. Percentage mortality of shoots before harvest in the fourth year were higher in the hybrid clone (32.1%) and in less productive clones of black poplar 107, 110, 202, 209 and 302 (35–50%), the mortality of the majority clones of black poplar ranged from 13.4% to 31.4% at SM. The mortality at BY was low because there were fewer but thicker shoots that did not compete with each other.

At SM the shoots within one clone were divided into classes according to diameters measured at a height of 0.5 m (Table 6). The shoots of diameter 19 mm or less were not included in this table because they are not harvested. The class 54–70 mm of shoot diameters is problematic for the harvesting machinery used at present. From this point of view other classes are relatively trouble free. The classes indicate the sum of volume indexes converted per plant. The volume index was calculated for each shoot from the measured diameter and from height derived from diameter ($D^2_{50}H$).

In NE-42 clone mainly a low number of thick shoots influences total volume index. Lateral shoots 20–53 mm in diameter accounted for 50% of the volume index of lateral shoots in almost 70% of black poplar clones. The most productive clones 301 and 206 belonged to these clones.

At BY this detailed analysis was not made with regard to fact that it is a less suitable area for planting black poplar.

Table 6
Division of lateral shoots according to their diameter at SM expressed as the sum of volume indexes (dm^3) converted per plant (2004)

Clone	Diameter lateral shoots (mm)					Σ of lateral shoots (dm^3)	Leading shoot (dm^3)	Percentage of lateral shoots
	20–36 (dm^3)	37–53	54–70	71–87	88⩽			
102	7.6	11.5	22.5	2.1	0.0	43.7	32.1	57.7
107	11.3	4.3	13.4	11.1	0.0	40.0	43.7	47.8
110	19.0	8.9	6.7	2.0	0.0	36.6	29.6	55.3
202	15.1	20.7	14.8	0.0	0.0	50.7	29.1	63.5
204	13.7	9.0	16.4	2.0	0.0	41.1	35.2	53.9
205	16.3	10.9	9.3	0.0	0.0	36.5	33.7	52.0
206	19.0	21.0	11.1	0.0	0.0	50.9	23.2	68.7
209	14.1	11.4	27.4	1.9	0.0	54.7	31.8	63.2
210	16.7	17.2	17.5	5.9	0.0	57.3	34.3	62.6
301	17.6	17.8	9.1	2.0	0.0	46.5	37.6	55.3
302	12.0	9.2	6.4	2.6	0.0	30.1	32.4	48.2
311	17.0	19.8	13.5	2.7	0.0	53.0	32.8	61.8
NE-42	7.7	2.3	15.5	32.5	3.7	61.7	59.6	50.9

Table 7
Average percentage of dry matter in fresh biomass at harvest at SM (March 2005)

Clone	Leading shoot	Lateral shoots	Average (%)
107	37.7	40.4	39.0
202	39.4	39.8	39.6
206	45.6	45.7	45.7
210	39.7	40.0	39.9
301	37.7	39.2	38.5
302	39.5	42.0	40.8
311	37.0	38.2	37.6
NE-42	41.0	43.4	42.2
Average	39.7	41.1	

3.4. Dry matter percentage in leading and lateral shoots at SM (Table 7)

The average value of dry matter percentage of leading shoots (39.7%) is not significantly lower than the dry matter percentage of lateral shoots (41.1%). Analysing these values in the particular clones, the percentage of dry matter of leading shoots is always lower than or identical to lateral shoots.

Only best clones of black poplar are reported.

3.5. Proportion of lateral shoots in total dry weight at SM (Table 8)

In the majority clones of black poplar the percentage of dry weight of lateral shoots in total dry weight ranged from 74.6 to 62.8 while in NE-42 this proportion was 54.7%. In the lowest productive clones of black poplar (107 and 302) lateral shoots contributed only 53% to total yield of dry matter.

Only best clones of black poplar are reported.

Table 8
Percentage of lateral shoots in total yield of dry matter at SM (2001–2004)

Clone	Dry matter (kg plant^{-1})			Percentage of dry matter of lateral shoots
	Total	Leading shoot	Lateral shoots	
107	12.0	5.6	6.4	53.3
202	12.1	3.9	8.2	67.8
206	13.8	3.5	10.3	74.6
210	13.2	4.9	8.3	62.9
301	14.3	4.9	9.4	65.7
302	11.8	5.5	6.3	53.4
311	12.9	4.2	8.7	67.4
NE-42	17.0	7.7	9.3	54.7

3.6. Relationship between dry matter yield and yield traits (Table 9)

The relationship between yield traits (plant height, diameter of leading shoot, number of shoots) and dry matter yield was examined by Spearman rank correlation test. The correlations were determined by the quality of soil and climatic conditions. In more favourable conditions (SM) where a higher number of shoots was formed, this trait had a crucial influence on dry matter yield in black poplar (a highly significant correlation between the number of shoots and dry matter yield was proved). However, for plant height and leading shoot diameter the correlation was not significant in any tested clones. But volume index (HD^2) was correlated with dry matter yield significantly. Another studied trait was the sum of volume indexes of particular shoots from one plant ($SVI = \Sigma HD^2$). The correlation of this trait with dry weight was highly significant.

Table 9
Relationship between dry matter yield and yield traits

Relationship between traits	r_s	
	SM	BY
Leading shoot height (*H*)—total yield of dry matter	ns	ns
Leading shoot diameter (D^2)—total yield of dry matter	ns	0.7678
Number of shoots[a]—total yield of dry matter	0.9182	ns
HD^2—total yield of dry matter	0.6969	ns
Σ (HD^2)—total yield of dry matter	0.7788	—
Leading shoot height (*H*)—yield of dry matter of leading shoot	0.9151	—
Leading shoot diameter (D^2)—yield of dry matter of leading shoot	0.9363	—
HD^2— yield of dry matter of leading shoot	0.8666	—
	$tab_{0.01} = 0.765$; $tab_{0.05} = 0.632$	$tab_{0.05} = 0.714$

Spearman rank correlation test.
[a]For *P. nigra* only.

Table 10
Occurrence of *Melampsora larici-populina* at SM and BY 2003

Clone	SM		BY	
	n	Points	*n*	Points
102	16	0.59	6	3.73
107	19	0.63	7	1.37
110	15	0.96	8	2.89
202	12	0.72	12	0.81
204	18	1.00	12	3.64
205	12	2.30	7	3.79
206	20	0.87	13	0.99
209	20	0.62	10	2.82
210	17	1.15	16	3.25
301	19	0.71	9	1.06
302	14	0.34	5	4.01
311	14	2.02	7	3.37
NE-42	19	0.26	15	0.01

At SM was also examined the relationship between dry weight of leading shoot and the height and diameter of leading shoot. There were highly significant correlations for both traits and volume index with dry matter yield.

In less favourable conditions (BY) where the number of shoots was low, the trait diameter of the leading shoot played an important role, i.e. there was a significant correlation between this trait and dry weight. Correlations with other traits were not significant.

3.7. *Occurrence of the rust Melampsora larici-populina Kleb. (Table 10)*

The presence of this important disease occurring in the genus *Populus* was evaluated periodically every year according to a point scale. The last evaluation was done every year at the time when the increments of plant height were zero, i.e. at the end of September. The intensity of rust occurrence fluctuated in the years of observation but the rank of clones according to the degree of infection was at SM mostly maintained. Clone NE-42 was highly resistant to this disease. Compared to clone NE-42 many clones had lower resistance but this was not significant.

At BY the rust occurrence during the observed term was higher than at SM. The clones 202, 206 and 301 had the highest resistance against the rust both at BY and SM. These clones were highly resistant also in other years of our observation.

4. Discussion

The tested clones of black poplar were not bred for SRC. Biomass yield ranged from 2.2 to 9.8 $t\,ha^{-1}\,yr^{-1}$ at the end of the second rotation (2001–2004); this productivity was achieved on less fertile soils in conditions of extensive plantation. Other authors reported yields in the range of 1.2–35 $t\,ha^{-1}\,yr^{-1}$ [4,6,15,16] but this high yield is concerned to localities with optimal conditions. The results of these authors were given for various species of the genus *Populus* and different soil, climatic and growing conditions, which explains such a high variability in yield.

In conditions with higher content of nutrients (fertilised plot), lower amount of precipitation and higher pH (6.7) at SM the yield of the best clones of black poplar approached the yield of hybrid clone NE-42 and average yields in other trials. In conditions with low content of nutrients (without fertilisation) but high groundwater level and low pH (5.0) at BY the yield of black poplar clones amounted to 50% and less of the yield in the hybrid clone. It is to note that the yield of NE-42 was higher in these conditions compared to conditions with higher nutrient content but lower moisture content. A certain distortion may be explained by above-average summer temperatures in the years of observation when the lower summer temperatures typical of the given locality could not exert their influence.

These results and previously published results [7] indicate that the tested clones of black poplar have higher nutrient requirements compared to the control hybrid clone, they do not tolerate acid soils and they require less amount of water. These results explain why the clones of black poplar were worse in condition at BY.

Crop organisation (number of planted cuttings) influences biomass yield substantially [10–14]. Most SRC crops are established by planting about 10 000 cuttings per ha. But a high number of cuttings markedly increases the cost of crop establishment. Our trial was established at a density equivalent to 2222 plants per ha. The lower crop density was used because it was assumed that the *P. nigra* had high light requirements [17]. It was possible to use a lower number of plants because rooted plants were used and the total mortality after eight years is low (0–30% in more favourable conditions; 0–50% in extreme conditions). The current trial biomass yields were comparable with the yields achieved in a crop with an initial density of 10 000 plants and harvested at the same age [6].

A comparison of black poplar with the hybrid clone in the traits plant height and leading shoot diameter showed that the leading shoot was significantly thicker in the hybrid clone compared to almost all clones of black poplar and the plant height was significantly taller in comparison with most clones of black poplar. These differences are still larger in the trait volume index. Higher values of the above-mentioned traits may be a result of heterosis effect in hybrid clones. But the higher performance of hybrid clones need not to be a rule [6].

In the trait number of shoots per plant the difference was in favour of black poplar, both in the first year after harvest and after 4 years before the second harvest. The best clones of black poplar formed a significantly higher number of shoots and these differences were significant before harvest. This phenomenon is probably of more general importance [6]. During 4 years a decrease in the number of shoots was logically lower than in denser stands [6] due to the lower competition between plants. The proportion of lateral shoots in total volume index and the proportion of dry matter of lateral shoots in total yield of dry matter document the importance of this trait for black poplar. In less favourable conditions when a low number of lateral shoots was formed, black poplar yield decreased significantly. Should be noted that in many clones relatively thin shoots are important for total biomass volume.

Thinner shoots have a relatively higher proportion of bark compared to wood. But bark has a higher concentration of inorganic elements and ash, relative to wood [18]. Therefore, thinner shoots may be undesirable especially when biomass is processed into pellets. The actual diameter of shoots is an important consideration with respect to harvest mechanisation.

The contribution of plant height, shoot diameter and shoot number to the formation of biomass yield is different in black poplar clones and in the hybrid clone, and in localities with different soil and climatic conditions. In more favourable conditions the number of shoots per plant contributed significantly to biomass yield in black poplar clones as indicated by a significant correlation. On the other hand, the correlation between the diameter of leading shoot or plant height and biomass yield was not significant. It is a logical result because the contribution of the leading shoot to total yield was lower as documented by the contribution of lateral shoots to biomass yield. Volume index correlates highly significantly with biomass yield; similarly, the sum of volume indexes of all shoots of a given clone is in high correlation with biomass yield. The latter trait that involves all three main traits may be used to estimate yield non-destructively.

A comparison of black poplar clones with the hybrid clone indicates that shoot diameter is of lower importance for yield formation in black poplar. It also applies in the environment when black poplar forms a low number of shoots. From this aspect such cultural practices can be recommended that promote higher shoot formation, e.g. lower density of plants.

A separate problem is the relationship between biomass yield and the occurrence of *Melampsora larici-populina* Kleb. This rust did not cause any great damage to plants in our trials, and clones with high resistance to rust belonged to clones with the highest biomass yield. Less dense spacing within the trial may be one of the reasons why the effects of the rust were less negative. But in denser crops a higher occurrence of rust was observed. The hybrid clone was characterised by higher resistance than the black poplar clones. Successful selection of resistant clones of black poplar and transfer of this resistance to progeny indicate that it will be possible to breed resistant clones within the species *P. nigra* [19].

5. Conclusion

In the course of 7 years we acquired the first knowledge of black poplar behaviour in SRC in two localities in marginal conditions. At the second harvest dry matter yield approached the yield of hybrid clone NE-42 at a crop density equivalent to 2222 plants ha^{-1}. Black poplar did not grow well on acid soils (pH = 5) with the high groundwater level while the growth of NE-42 clone was good on these soils. The number of lateral shoots in black poplar contributed to dry matter yield significantly. In high-yielding clones of black poplar the proportion of dry weight of lateral shoots in total weight was between 66% and 75% while in NE-42 clone it amounted to 55%. Lateral shoots 20–53 mm in diameter accounted for 50% of the volume index of lateral shoots in almost 70% of black poplar clones. The sum of volume indexes of all shoots of a given clone is in high correlation with biomass yield, therefore it can be used as a non-destructive method for yield estimation. Higher number of shoots and lower infection of plants by the rust *Melampsora larici-populina* may be connected with lower density of plants.

Acknowledgement

This paper was supported by Grant 0002707301 of the Ministry of Environment of CR.

References

[1] Directory of poplar and willow experts. Register of *Populus* L. cultivars. Databases F.A.O. Instituto di Sperimentazione per la Pioppicultura; 2000.

[2] Laureysens I, Deraedt W, Indeherberge T, Ceulemans R. 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 and Bioenergy 2003;24:81–95.

[3] Heilman PE, Stettler RF. Genetic variation and productivity of *Populus trichocarpa* T. & G. and its hybrids. II. Biomass production in a 4-year plantation. Canadian Journal of Forest Research 1985;15:384–8.

[4] Scarascia-Mugnozza GE, Ceulemans R, Heilman PE, Isebrands JG, Stettler RF, Hinckley TM. 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. Canadian Journal of Forest Research 1997;27:285–95.

[5] Rogers DL, Stettler RF, Heilmann PE. Genetic variation and productivity of *Populus trichocarpa* and its hybrids. III. Structure and pattern of variation in a 3-year field test. Canadian Journal of Forest Research 1989;19:372–7.

[6] Laureysens I, Pellis A, Willems J, Ceulemans R. Growth and production of a short rotation coppice culture of poplar. III. Second rotation results. Biomass and Bioenergy 2005;29:10–21.

[7] Benetka V, Bartáková I, Mottl J. Productivity of *Populus nigra* L. ssp. *nigra* under short-rotation culture in marginal areas. Biomass and Bioenergy 2002;23:327–36.

[8] Rae AM, Robinson KM, Street NR, Taylor G. Morphological and physiological traits influencing biomass productivity in short-rotation coppice poplar. Canadian Journal of Forest Research 2004;34: 1488–98.

[9] Wu R, Stettler RF. Quantitative genetics of growth and development in *Populus*. II. The partitioning of genotype × environment interaction in stem growth. Heredity 1997;78:124–34.

[10] DeBell DS, Clendenen GW, Harrington CA, Zasada JC. Tree growth and stand development in short-rotation *Populus* plantings: 7-year results for two clones at three spacings. Biomass and Bioenergy 1996;11:253–69.

[11] Armstrong A, Johns C, Tubby I. Effect of spacing and cutting cycle on the yield of poplar grown as an energy crop. Biomass and Bioenergy 1999;17:305–14.

[12] Fang S, Xu X, Lu S, Tang L. Growth dynamics and biomass production in short-rotation poplar plantations: 6-year results for tree clones at four spacings. Biomass and Bioenergy 1999;17:415–25.

[13] Larocque GR. Performance and morphological response of the hybrid poplar DN-74 (*Populus deltoides* × *nigra*) under different spacings on a 4-year rotation. Annales Forest Science 1999;56:275–87.

[14] Proe MF, Griffiths JH, Craig J. Effects of spacing, species and coppicing on leaf area, light interception and photosynthesis in short rotation forestry. Biomass and Bioenergy 2002;23:315–26.

[15] Beale CV, Heywood MJ. Productivity of commercial crops of short rotation coppice at six sites in southern England. Aspects of Applied Biology 1997;49:181–8.

[16] Strong T, Hansen E. Hybrid poplar spacing/productivity relations in short rotation intensive culture plantations. Biomass and Bioenergy 1993;4:255–61.

[17] Mottl J, Dušek J. Specification of growing areas of poplars for ladscaping purposes. Průhonice: MS. Research Institute of Ornamental Gardening; 1991 140pp.

[18] Tharakan PJ, Volk TA, Abrahamson LP, White EH. Energy feedstock characteristics of willow and hybrid poplar clones at harvest age. Biomass and Bioenergy 2003;25:571–80.

[19] Benetka V, Šálková I, Vrátný F. Selection of clones of *Populus nigra* L. ssp. *nigra* for resistance to *Melampsora larici-populina* Kleb. Rust Journal of Forest Science 2005;51:161–7.