BIOMASS AND GASIFICATION PROPERTIES OF YOUNG *POPULUS* CLONES

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ABSTRACT

Studies were conducted to establish baseline information for use in characterizing poplar clones (*Populus* spp.) as an energy or fiber feedstock. Size and survival of 4-year-old trees varied significantly among the 29 clones evaluated, but larger trees generally had the best survival and are highly important in clonal comparisons. The high average mortality indicated that coppicing as a management strategy to grow these clones for fiber is questionable, at least with the clones being tested. Characteristics of the wood were similar to those of soft hardwoods; the mean value of gross heat of combustion was 18.9 kJ/g (4,520 cal/g); the fiber length was relatively short (0.84 mm); the ash content was 0.39%; and the specific gravity was 0.37. Mean specific gravity values for the bark and wood were 0.37 at the tree base and 0.34 at dbh (all based on green volume).

In general, wood was lower in gross heat of combustion and higher in ash content than bark, but specific gravity did not differ significantly. The whole-tree bark/wood heat of combustion was between the values for the two components. Chemical properties between selected clones were not different.

Steam gasification of four poplar clones (selected from the better clones) conducted in a fluidized-bed, bench-scale reactor over a temperature range of 595 to 617°C showed no significant differences among them. The response variables considered were dry gas composition, gas higher heating value, dry gas volumetric and mass yields, carbon conversion to gas, and energy recovery.

Keywords: *Populus*, wood energy, specific gravity, gross heat of combustion, fiber length, gasification, gas yield, tree growth.

INTRODUCTION

Intensive culture of trees has attracted much interest because of envisioned fiber shortages and the use of wood for energy. Short rotation intensive culture forestry (SRIC) is an agronomic system designed to maximize wood production per unit of land using genetically improved stock and near-optimal growing conditions (Dawson 1979). Presently SRIC is used commercially with *Populus* hybrids in the Pacific Northwest. High fiber yields in a short period of time are its major attributes. *Populus* is studied worldwide because of its fast growth potential. Many hybrids have been grown in Europe, North America, South Asia, and elsewhere.

Research has shown that certain clones grow well under SRIC and are established easily (Phelps et al. 1982). When the potential for

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industrial use is evaluated, both growth and wood quality characteristics are important. The raw material may differ in properties and intrinsic wood quality (Phelps et al. 1982) between its parts (bark and wood of stems and branches) and the whole tree or between clones.

The objective of this study was to evaluate the growth and material quality of selected *Populus* clones grown utilizing SRIC by comparing biomass characteristics, bark and wood properties, chemical differences, and gasification behavior among clonal sources.

MATERIALS AND METHODS

Planting site and measurements

This study was conducted in eastern Kansas on a level, lowland site, which had been abandoned from farming for 45 years. The soil was classified in the Eudora silt loam series (coarse-silty, mixed, mesic, Fluventic Hapudolls) and consisted of 25 cm of silty loam soils underlain by very fine sandy loam. Thirty *Populus* clones (Table 1.) from cuttings were planted on this site at a 1.2- × 1.2-m spacing (6,725 trees/ha) in a completely randomized design with ten replications of individual trees. All clones were under consideration for use in biomass plantations. Those selected were among the more promising of the various short-term trials in Kansas. The plantation was cultivated during the 6-year course of this study.

Nondestructive measurements of height and diameter during the dormant season were used with individual tree weight curves to determine dry weight tree yields of both the original and coppice stems. These curves (Geyer 1993) were developed from destructive sampling of 85 trees at similar spacings, giving the following equation with a correlation coefficient of 0.991:

$$\log_{10}W = 1.979 + 0.9378 \log_{10}D^2H, \quad (1)$$

where W is oven-dried (OVD) tree weight (kg), D is base diameter (cm), and H is total height (m). We have found the coefficient values to be different for black locust (Geyer et al. 1994), silver maple (Geyer and Walawender 1997), Siberian elm (Geyer et al. 1987), catalpa (Geyer and Walawender 1999), and 10 other hardwood trees species not yet reported.

TABLE 1. *Identification of* Populus *clones.*

Source[1]	Clone #	Parentage (origin)
1	62C	*P. deltoides* (Illinois)
2	Seedling	Same (Missouri)
3	70C	Same (Kansas)
4	232C	Same (Missouri)
5	232C	Same (Missouri)
6	254C	Same (Missouri)
7	243C	Same (Missouri)
8	259N	Same (Missouri)
9	KSTC	Same (Kansas)
10	NE237	Unknown (North Eastern Forest. Exp. Station)
11	LW8	*P. deltoides* (Kansas)
12	NE17	Unknown (North Eastern Forest. Exp. Station)
13	None	None
14	NE20	Unknown (North Eastern Forest. Exp. Station)
15	NE254	*P. deltoides* cv. Angulata × *P. trichocarpa*
16	NE222	*P. deltoides* cv. Caudina
17	NE238	*P. deltiodes* × *P. nigra* 'Volga'
18	NE264	*P. deltoides* × *P. nigra* 'Volga'
19	NE367	*P. deltoides* × *P. nigra* 'Volga'
20	Miss74	*P. deltoides* (Mississippi)
21	S.Dk.Sx	Same (Nebraska)
22	279N	Same (Illinois)
23	52C	Same (Ohio)
24	181N	Same (Minnesota)
25	249C	Same (Missouri)
26	MO1	Same (Missouri)
27	Miss66	Same (Mississippi)
28	Miss109	Same (Mississippi)
29	KS	Same (Kansas)
30	LW5	Same (Kansas)
31	259C	Same (Missouri)

[1] Kansas State University number.

Sampling and analyses.—Trees were cut after four growing seasons, and disks for characterization were taken, from four samples of each, from the eleven largest clones that had survival in the upper third of source #'s 1, 2, 6, 7, 8, 16, 17, 18, 21, 22, 26. Disks of 5-cm thickness from the base, dbh, and from the midpoint level of six major branches were analyzed separately. All bark and wood properties, except the chemical characteristics, were based upon these disks. The data were analyzed using analysis of variance and simple correlation procedures with SAS.

Chip source for gasification studies.—Approximately 1.5 kg of chips were obtained from each of the four largest trees randomly selected from the 11 clones used in the screening; trunk diameters ranged from 5 to 12 cm. The whole-tree chips were obtained from dormant stems and branches; they contained a substantial portion of bark. The trees were chipped in their entirety with a MORBARK EEGER BEEVER chipper. Further reduction of particle size was accomplished by passing the chips through a Fritzmill with a 1.651-mm screen. The resulting ground material was separated by sieves to obtain the −28 to +50-mesh (0.595 to 0.287-mm) fraction. Fibrous materials from bark (less than 1%), which would result in bridging in the feed hopper, were removed in the separation process. Further reduction of the particle size was accomplished by passing the sieved fractions through a Fritzmill with a 0.508-mm screen.

Gross heat of combustion.—This was determined for ground, oven-dried disk samples according to ASTM D 2015-77 (1981). The material used for the evaluation was ground to pass through a 20-mesh screen to achieve complete combustion and good pellet cohesion (Neenan and Steinbeck 1979). Samples from four trees per clone, each consisting of approximately one gram of milled material, were pressed into pellets and combusted in a Parr 1341 adiabatic calorimeter. Correction factors for the formation of acids were not included in the calculations of gross heat of combustion (Murphey and Cutter 1974; Barnes and Sinclair 1984). However, heating values were corrected for moisture regained during storage.

Specific gravity.—The specific gravity was determined on the basis of oven-dried weight per green volume of the individual disk segments (¼ section void of branch traces). Green volumes were obtained by soaking disk segments for 10 days in water until constant volume was achieved. Excess moisture was removed from the surface of the segment with a damp cloth, and each segment's water displacement (volume) was measured. Then segments were oven-dried at 104°C for 3 to 4 days to constant weight to determine the dry sample weight. Bark, wood, and wood and bark evaluations were made.

Ash content.—Samples of each clone from disks taken at the stem and branches were oven-dried, ground, and ashed in a muffle furnace. Ash contents of the bark, wood, and combined samples were determined pursuant to the ashing procedure described in ASTM D 1102-84 (1995).

Fiber length.—Fiber length was determined using a method similar to that of Tsoumis (1968). Matchstick-size slivers taken from chips were macerated, and separate fibers were projected with a Mark VII microprojector for measurement. Five fibers on each of 20 slides were measured and recorded.

Gasification.—A bench-scale, fluidized-bed reactor was used to conduct steam gasification experiments and to determine the gasification characteristics of the selected clones. The reactor system used in this work was designed for investigating the gasification of carbonaceous materials at temperatures up to 1130°C under atmospheric pressure conditions. Details of the bench-scale gasifier are given by Neogi (1984).

The operating conditions for the experimental runs are summarized in Table 2. The reactor temperature varied slightly and ranged from 595 to 617°C. The steam rate varied from 13.1 to 14.2 g/min, and the feed rate varied from 2.1 to 2.5 g/min. Thus, the steam-to-feed ratio ranged from 5.6 to 6.6. The flow rate for the nitrogen purge (at 25°C and 101.3 kPa) varied from 0.00226 to 0.00232 m^3 min, and the gas phase residence time varied from 4.8 to 5.1 s. The order in which the experiments at the various temperatures were performed was randomized.

Gas compositions were averaged over the last 50 to 60 min of steady-state operation in each run. The gasification characteristics or re-

TABLE 2. *Reactor operating parameters for whole-tree chips of* Populus *clones.*

Source	Run	N_2purge (m^3/min)	Steam rate (g/min)	Feed rate (g/min)	S/F[1]	r^2 (sec)	Temperature ©
02	1	0.00233	14.1	2.44	5.78	4.89	595
	2	0.00233	14.1	2.14	6.59	4.94	604
21	1	0.00226	13.1	2.27	5.77	5.12	607
	2	0.00226	14.1	2.27	6.21	4.85	612
22	1	0.00230	14.1	2.50	5.64	4.80	606
	2	0.00230	13.7	2.43	5.64	4.83	617
26	1	0.00226	14.2	2.40	5.92	4.81	604
	2	0.00230	13.9	2.25	6.18	4.90	613
Mean		0.00229	13.9	2.34	5.97	4.89	607

[1] S/F = steam-to-feed mass ratio.
[2] r = gas phase residence time.

sponse variables in this part of the work were the dry gas composition (major components: H_2, CO_2, CO, and CH_4); the gas higher heating value (HHV); dry gas volumetric and mass yields; the carbon conversion to gas; and energy recovery (the percentage of the energy content of the feed recovered as gas). The methods for evaluating each of the above mentioned gasification characteristics have been detailed by DeWyke (1989a).

RESULTS AND DISCUSSION

Biomass characteristics

In this study, we assessed the total material available and the biomass quality of poplar grown under SRIC from the whole-tree utilization standpoint. Four-year-old trees averaged 6.9 m in height, 9.1 cm in diameter, and 44% survival (Table 3). Use of cuttings for establishment in Kansas is somewhat questionable because of the variable patterns of spring moisture. The largest clone (source #17) was 12 times the D^2H (base diameter^2 × total height) volume of the smallest clone (source #28), 2.3 times larger in base diameter, and 2.7 times taller in height. These characteristics varied greatly among clones and were significantly different (Table 4). Note that the D^2H volume is related to dry weight yield. The comparisons of pure *P. deltoides* vs. hybrids were not of major importance. The highest D^2H and best survival were used as criteria to select the 11 best clones for wood property analysis (source #s 1, 2, 6, 7, 8, 16, 17, 18, 21, 22, 26).

Two-year-old sprouts averaged 4.3 m tall and 2.3 cm in diameter. Average survival dropped to 14%—a 30% loss. Three of the better clones (source #s 8, 21, and 26) retained high survival (50%) even after being cut once. Unlike other species that can be cut several times (Geyer 1985), coppicing poplar numerous times is questionable. No significant relationship was found between sprout growth and cut-stump diameter at 4 years.

Wood properties

Because wood quality characteristics of the various portions of the tree may differ, the quality of the final whole-tree material also may be affected. Thus, we evaluated each clone from the disks: each portion of the 11 selected clones by source, cut disk level, wood vs. bark composition, and pure vs. hybrid stock. Wood characterizations (Geyer et al. 1987, 1994; Geyer and Walawender 1997, 1999) have been published previously for other young tree species.

All of the wood properties determined and statistical analyses are summarized in Tables 5 and 6, respectively. The average gross heat of combustion of all 11 *Populus* clones (bark and wood) was 18.8 kJ/g (4,457 cal/g), which is 4½% lower than the average of 19.7 kJ/g reported for hardwoods (Panshin and deZeeuw 1980). This value is within the ranges for hardwoods quoted by Arola (1976), which varied from 16.3 kJ/g (3,886 cal/g) for white ash to 23.9 kJ/g (5,728 cal/g) for birch. Panshin and deZeeuw (1980) comment that the value of heat of combustion bears little relationship to a particular kind of wood and varies from 5% to 8%. No significant difference was found between clonal sources, but values for position level within a tree were different (5% level); branches were greatest at 18.9 kJ/g. Wood was lower (18.2 kJ/g) than bark at the 5% level. No significant difference

TABLE 3. *Clonal ranking based on index of volume D^2H (where D is the base diameter and H is the total height of all 4-year-old* Populus *clones.*

	4 year seedlings[1]				2 year sprouts[1]				
Source #	Ht (m)	Base d (cm)	D^2H	Sur. (%)	Ht (m)	Spr. (#)	Dom. (#)	D^2H	Sur. (%)
17[2]	**7.1**	**13.0**	**606a[3]**	**50**	**4.2**	**3.7**	**2.3**	**102**	**30**
22	**7.4**	**11.0**	**592ab**	**60**	**4.5**	**2.0**	**1.7**	**238**	**30**
21	**7.4**	**12.0**	**557abc**	**100**	**3.9**	**3.3**	**1.7**	**113**	**70**
02	**7.8**	**10.9**	**513abcd**	**60**	**4.3**	**2.0**	**1.3**	**132**	**40**
26	**8.3**	**10.7**	**496abcd**	**60**	**5.9**	**3.3**	**1.5**	**233**	**60**
23	7.6	9.1	442abcde	30	4.0	2.3	1.7	104	30
14	7.8	10.2	440abcde	20	1.8	1.0	1.0	002	10
08	**7.4**	**9.9**	**369abcdef**	**50**	**5.3**	**4.2**	**2.4**	**193**	**50**
18	**6.9**	**9.9**	**366abcdef**	**70**	**2.2**	**1.7**	**1.3**	**12**	**30**
16	**7.1**	**9.4**	**356abcdef**	**60**	**4.9**	**1.5**	**1.5**	**79**	**20**
25	7.0	9.7	351abcdef	30	4.9	2.0	1.3	140	30
31	8.0	9.1	350abcdef	20	5.1	2.5	2.0	102	20
29	7.3	9.1	314abcdef	20	3.4	3.0	2.0	42	10
03	6.5	8.9	286abcdef	40	4.4	2.0	1.3	58	30
30	7.4	8.4	275abcdef	40	4.0	2.0	1.5	52	40
11	7.4	8.1	262abcdef	30	3.8	2.0	1.0	42	20
19	5.6	9.4	256abcdef	20	—	—	—	—	0
07	**7.2**	**7.9**	**235abcdef**	**60**	**4.8**	**1.3**	**1.3**	**66**	**40**
06	**5.6**	**8.4**	**231abcdef**	**60**	**2.7**	**1.0**	**1.0**	**10**	**10**
24	6.0	8.4	223abcdef	50	3.6	2.0	1.0	50	20
04	6.6	7.6	218cdef	40	3.1	1.0	1.0	23	30
01	**6.6**	**7.6**	**209cdef**	**90**	**4.2**	**1.5**	**1.0**	**42**	**20**
09	6.2	7.6	195cdef	40	—	—	—	—	0
15	5.2	8.4	185cdef	10	—	—	—	—	0
20	4.8	6.9	173cdef	60	4.9	1.3	1.3	126	30
05	6.1	6.1	138def	50	4.9	2.0	1.0	85	10
27	6.4	5.6	102ef	10	4.9	1.0	1.0	48	10
28	2.6	6.1	49f	10	2.9	1.0	1.0	11	10
10	—	—	—	0	—	—	—	—	0
12	—	—	—	0	—	—	—	—	0
Mean	**6.9**	**9.1**	**345**	**44**	**4.3**	**2.3**	**1.5**	**105**	**14**

[1] Ht = total tree height, Base d = base diameter, D^2H = base diameter^2 × total height, Sur. = survival, Spr. = total number of sprouts, Dom. = number of dominant sprouts.
[2] Bold type indicates 11 best clones selected for characterization of wood properties.
[3] Means with the same letter are not significantly different at the 0.05 level.

was found between the pure *deltoides* and the hybrid sources. In a similar test of 7 clones, Blankenhorn et al. (1985) found no significant difference between wood and wood and bark at age four; they also found that bark had greater heat of combustion than wood.

The mean ash content of the poplars (bark and wood) was 1.14% based on oven-dry weight. Normally, ash content of wood from various tree species ranges from 0.1% to 0.5% (Panshin and deZeeuw 1980). However, bark ash content can be as much as 10 times greater (Jenson et al. 1963). Therefore, one can expect the ash content of the entire disk (containing bark and wood) to fall between the two values, depending upon the percentage of each constituent. In our study, bark ash was 4.40% and wood ash was 0.39%. Branches were greater at 1.69% vs. 1.16% and 1.04% for the base and dbh, respectively. Ash content differed significantly among clones, but not between the comparison of hybrids. Blankenhorn et al. (1985) found bark to have 3 to 4 times greater ash content than wood and also found significant differences among the 7 clones they tested at 4 years of age.

TABLE 4. *F values and levels of significance for seedling and sprout growth for all clones and pure* P. deltoides *vs. hybrids.*

	All clones		Pure vs. hybrids	
	F value	Pr > *F*	*F* value	Pr > *F*
Seedlings				
Total height	2.33	0.0015	0.00	0.9736
Base diam.	2.65	0.0003	5.55	0.0201
D^2H	2.63	0.0003	2.02	0.1575
Sprouts				
Total height	2.18	0.0117	5.64	0.0204
Total # sprouts	1.23	0.2650	0.03	0.8697
# dominants	0.92	0.5742	0.55	0.4593
D^2H	1.55	0.1016	2.50	0.1182

The average wood fiber length was 0.84 mm. Panshin and deZeeuw (1980) reported fiber lengths for aspen poplars to range from 1.32 to 1.38 mm, and Phelps et al. 1982 reported lengths from 0.58 to 0.70 mm 4-year-old *P. deltoides* hybrids. We found that the fiber lengths of the branches were longest, those at the base were next, and those at breast height were the shortest.

Specific gravity (SG) of the individual disk segments for bark and wood combined was 0.37, with no difference between the two separately. Geyer (1981) reported that SG ranged from 0.33 to 0.42 for mixtures of stems, branches, bark, and buds from 3-year-old trees of ma-

TABLE 5. *Properties (mean values) of 11 selected* Populus *clones.*

Source (#)	Heat (kJ/g)	Ash (%)	Fiber[1] (mm)	SG	Ht. (m)	Dbh (cm)	Weight Tot. (kg)	Weight Stem (%)	Weight Brc. (%)	Sample Size
Source (Kansas #)										
1	18.7	1.50a[2]	0.85	0.40a	7.5bc	5.8	20.9	60	26	4
2	18.8	1.18bcd	0.83	0.38bc	8.2abc	8.1	29.2	67	33	4
6	18.4	0.91e	0.83	0.38b	6.2d	6.1	15.6	60	40	4
7	18.6	1.36ab	0.81	0.37bc	7.3cd	6.1	14.9	67	33	4
8	18.1	0.96e	0.82	0.36ef	8.0abc	7.6	18.5	72	28	4
16	19.2	1.09cde	0.87	0.38bc	7.7abc	6.1	13.8	80	20	4
17	18.6	1.24bc	0.85	0.35fg	7.8abc	7.6	20.5	69	31	4
18	18.1	1.08cde	0.85	0.37bc	7.7abc	6.9	18.6	71	29	4
21	18.9	1.01de	0.84	0.34g	8.2abc	7.6	26.9	74	26	4
22	18.6	1.06cde	0.76	0.36de	8.8a	10.2	41.1	62	38	4
26	18.9	1.15cde	0.84	0.37cd	8.8a	8.6	27.9	72	28	4
Mean	18.8	1.14	0.84	0.37	7.8	7.4	22.5	68	32	—
Sign.	NS[3]	**	NS	*	**	—	—	—	—	—
Level (position)										
Base	18.4b	1.16b	0.91a	0.37b	—	—	—	—	—	44
Dbh	18.4b	1.04b	0.92a	0.34c	—	—	—	—	—	44
Bran.	18.9a	1.69a	0.67b	0.40a	—	—	—	—	—	44
Sign.	*	*	*	*	—	—	—	—	—	—
Composition (raw material)										
Bark	18.9a	4.40a	—	0.37a	—	—	—	—	—	44
Wood	18.2c	0.39c	—	0.37a	—	—	—	—	—	44
Comb.	18.8b	1.14b	—	0.37a	—	—	—	—	—	44
Sign.	*	*	—	NS	—	—	—	—	—	—
Strain (type)										
Pure	18.6a	1.14a	0.83	0.37a	7.9a	7.6	24.6	67	33	32
Hybr.	18.7a	1.14a	0.86	0.36b	7.7a	6.9	17.7	72	28	12
Sign.	NS	—	—	*	—	—	—	—	—	—

[1] Fiber length of wood only; other properties are combined bark and wood.
[2] Means with the same letter are not significantly different at the 0.05 level.
[3] * = significance at the 0.05 level; ** = significance at the 0.01 level; NS = not significantly different.

TABLE 6. *F values and levels of significance for wood properties of 11 selected 4-year-old* Populus *clones.*

Property	*F* value	Pr > *F*	Sign.[1]
Fiber length—wood only (mm)			
Clones	1.30	0.2699	NS
Level	317.21	0.0001	S
Strain	—	—	—
Heating value—bark + wood (kJ/g)			
Clones	1.02	0.4493	NS
Level	18.3	0.0001	S
Composition	119.2	0.0001	S
Strain	0.24	0.6240	NS
Ash content—stem bark + wood			
Clones	2.61	0.0186	S
Level	38.59	0.0001	S
Composition	1047.19	0.0001	S
Strain	—	—	—
Ash content–stem bark only (%)			
Clones	4.70	0.0003	S
Level	9.87	0.0001	S
Composition	—	—	—
Strain	—	—	—
Specific gravity—stem wood only			
Clones	2.96	0.0091	S
Level	48.40	0.0001	S
Composition	1.40	0.2471	NS
Strain	3.86	0.0499	S
Specific gravity—branch wood only			
Clones	1.31	0.2643	NS
Levels	—	—	—
Composition	43.13	0.0001	S
Strain	—	—	—

[1] Significant/nonsignificant.

ple, sycamore, willow, black alder, boxelder, and two sources of cottonwood. In this work, the SGs of the clones were significantly different (5% level); with sources 1, 2, 6, 7, 16, 18, and 26 having the highest SG. Height levels (position—branches greatest) and type (strain—pure greatest) also showed significant differences in SG, but raw material composition (wood, bark, or combined) did not. Apparently, the bark and wood of poplars are of comparable density. Beaudoin et al. (1992) found clonal differences amongst 10 sources and greatest SG at the base of the stem in 9-year-old trees as we also found in our 4-year-old trees (Table 5).

Correlations of wood properties with tree size when cut at 4 years were not significant except for SG, where stump diameter, total height, and volume (D^2H) were significant at the 1% to 3% level, but with r^2 values less than 0.50.

Gasification studies

The chemical and physical properties of the whole-tree chips from clones 2, 21, 22, and 26 used for the gasification studies are summarized in Table 7. Statistical analyses for the differences in the properties of the selected clones were not conducted since heating values and ash contents were close and any clonal differences would not be reflected in the gasification characteristics, which was the focus of this part of the work. The methodology for obtaining the above properties is outlined in DeWyke (1989b). The ash content of 1.64% and the heating value of 19.25 kJ/g (4,565 cal/g) are higher than the values given earlier for wood because of the presence of a high proportion of bark from both stems and small branches.

The results from the gasification trials are summarized in Table 8. Analyses of the vari-

TABLE 7. *Chemical and physical properties of whole-tree chips of 4-year-old* Populus *clones used for gasification.*

Clone	Elemental composition[1] (% dry) C	H	O[2]	N	Ash	Moisture content[3] (% wet basis)	Heat of combustion[4] (kJ/g)
02	46.45	5.88	45.13	0.71	1.83	5.30	19.14
21	48.11	5.89	43.85	0.56	1.59	5.14	19.48
22	47.90	5.95	44.33	0.38	1.44	5.45	19.25
26	48.62	5.93	43.11	0.61	1.72	5.47	19.14
Mean	47.77	5.91	44.10	0.56	1.64	5.34	19.25

[1] Average of 6 samples for C, H, N, and O; 12 samples for ash.
[2] By difference.
[3] Average of 12 samples.
[4] Average of 4 samples from bomb calorimeter.

TABLE 8. *Analysis of variance for gasification trials of* Populus *clones.*

Dependent variable	Clone	Mean	MSE[1]	df_E[2]	Parameter	df	*F*-value	Pr > *F*
Higher heating value (MJ/m^3)	2	13.34	0.0480	3	Clone	3	0.84	0.5543
	21	13.45			Temp	1	9.15	0.0565
	22	13.58						
	26	13.59						
	Mean	13.49						
Moles % H_2	2	34.49	2.252	3	Clone	3	0.63	0.6421
	21	35.81			Temp	1	0.76	0.4463
	22	35.06						
	26	35.86						
	Mean	35.31						
Mole % CO_2	2	26.49	0.4471	3	Clone	3	2.27	0.2590
	21	26.93			Temp	1	8.08	0.0655
	22	26.26						
	26	26.72						
	Mean	26.35						
Mole % CO	2	27.00	2.020	3	Clone	3	1.49	0.3756
	21	24.50			Temp	1	1.37	0.3256
	22	25.83						
	26	25.70						
	Mean	25.76						
Mole % CH_4	2	7.579	0.4494	3	Clone	3	0.19	0.8948
	21	8.378			Temp	1	5.02	0.1109
	22	8.328						
	26	8.277						
	Mean	8.140						
Gas yield (m^3/kg DAF)	2	0.496	1.513×10^{-3}	3	Clone	3	3.31	0.1758
	21	0.590			Temp	1	0.61	0.4907
	22	0.634						
	26	0.599						
	Mean	0.580						
Mass yield (kg/kg DAF)	2	0.474	1.016×10^{-3}	3	Clone	3	4.12	0.1376
	21	0.553			Temp	1	1.05	0.3803
	22	0.597						
	26	0.556						
	Mean	0.545						
Carbon conversion (%)	2	37.84	4.673	3	Clone	3	3.99	0.1427
	21	46.56			Temp	1	0.45	0.5501
	22	46.75						
	26	42.81						
	Mean	42.49						
Energy recovery (%)	2	34.51	4.838	3	Clone	3	4.15	0.1366
	21	40.61			Temp	1	0.00	0.9685
	22	44.70						
	26	42.46						
	Mean	40.57						

[1] MSE = mean square error.
[2] df_E = degrees of freedom for mean square.

ables, the means for each clone, and other statistical parameters are shown in the table. None of the response variables showed significant differences at the 5% level among clones or temperatures. In previous tests with Siberian elm (Geyer et al. 1987), we found gas volumetric and mass yields, carbon conversion, and energy recovery to be temperature-dependent, but with only slight variation. The young poplar trees studied here were typical for most biomass materials. Comparison of these results for whole trees with regression curves established for cottonwood (*P. deltoides*) branches only (DeWyke 1989c) revealed that the data points fell within or were very near the 95% confidence intervals.

CONCLUSIONS

Our results suggest that biomass growth, bark and wood properties, and chemical characteristics should be considered when selecting *Populus* clones for SRIC. Comparisons indicated that some significant clonal effects were present.

1) Clonal differences in growth were readily apparent; the tallest one third were significantly greater in height (50%) than the smallest one third and 25% larger in diameter. Coppicing from cut stumps was low in the clones evaluated as compared to other broadleaf tree species. Thus if coppicing is important for establishing the next stand, then selection of good sprouting clones is necessary.

2) Wood and bark properties were similar to those of other soft hardwoods, such as catalpa, maple, willow, and yellow poplar. These results suggest that for the 11 clones included in this study, parentage affected ash content and specific gravity of the whole-tree (bark and wood) combination.

3) Steam gasification of young whole-tree poplar clones in a fluidized-bed yielded a medium energy gas, and clonal differences did not exist.

4) Coppice survival, tree size, specific gravity, and ash content exhibit significant clonal variation and should be considered when comparing hybrid poplar sources for SRIC plantations.

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