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Productivity of *Populus* in monoclonal and polyclonal blocks at three spacings

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Abstract: Four *Populus* clones were grown at three spacings (0.5, 1.0, and 1.5 m) in monoclonal plots and in polyclonal plots with all clones in intimate mixture. After the third year, many individual tree and stand traits differed significantly by clone, spacing, deployment method, and their interactions. Differences among clones in growth and stem form were greater in polyclonal than in monoclonal plots, and differences in performance between deployment methods were greater in the denser spacings. Monoclonal stands had greater uniformity in tree size than polyclonal stands. Total aboveground oven-dry woody yield averaged 48.0 Mg·ha^{-1} in the 0.5-m spacing and decreased as spacing increased. Some clones differed in yield from other clones in both monoclonal and polyclonal plots. Assuming that equal numbers of plants from the same clones were planted, the manner of deployment did not affect productivity; that is, although there were clonal differences in yield, mean yield of the four clones in monoclonal plots (44.3 Mg·ha^{-1}) did not differ from the yield of polyclonal plots (43.1 Mg·ha^{-1}). Comparative yields (yield in polyclonal plots/yield in monoclonal plots) differed substantially, however, and the increases or decreases in comparative yield differed with spacing and clone. Production and inventory were less evenly balanced among clones with polyclonal than with monoclonal deployment.

Résumé : Quatre clones de *Populus* furent cultivés dans un dispositif comportant trois espacements (0,5, 1,0 et 1,5 m) et des parcelles monoclonales et polyclonales où tous les clones étaient complètement mélangés. Après trois ans, plusieurs traits des arbres pris individuellement ou des peuplements différaient selon le clone, l'espacement, la méthode de déploiement et les interactions entre ces facteurs. Les différences dans la croissance et la forme de la tige entre les clones étaient plus importantes dans les parcelles polyclonales que monoclonales. Du point de vue de la performance, les différences entre les méthodes de déploiement étaient plus fortes dans les plantations les plus denses. Les peuplements monoclonaux étaient plus uniformes quant à la dimension des arbres que les peuplements polyclonaux. Le rendement total épigé de matière ligneuse sèche atteignait en moyenne 48,0 Mg·ha^{-1} avec l'espacement de 0,5 m et diminuait avec l'augmentation de l'espacement. Le rendement de certains clones différait de celui d'autres clones dans les parcelles monoclonales et polyclonales. En assumant qu'on a planté le même nombre de plants pour les clones correspondants, le mode de déploiement n'a pas affecté la productivité; c'est-à-dire que, même s'il y avait des différences de rendement entre les clones, le rendement moyen des quatres clones en parcelles monoclonales (44,3 Mg·ha^{-1}) ne différait pas du rendement des parcelles polyclonales (43,1 Mg·ha^{-1}). Les rendements comparatifs (rendement dans les parcelles polyclonales/rendement dans les parcelles monoclonales) différaient par contre beaucoup et les augmentations ou les diminutions de rendement comparatif différaient selon l'espacement et le clone. La production et les stocks étaient moins également répartis entre les clones dans le cas des déploiements polyclonaux que monoclonaux.
[Traduit par la Rédaction]

Introduction

Short-rotation intensive culture (SRIC) of clonal poplar and willow plantations has advanced from a theoretical concept to a viable fiber and biomass production system through strong research and development efforts in North America (Ranney et al. 1987; Richardson 1989) and Europe (Christersson et al. 1993). In the northwestern United States, research on genetics and physiology has produced many hybrid poplar clones (Stettler et al. 1988; Hinckley et al. 1989) that are very productive when planted on suitable sites using appropriate cultural techniques (Heilman et al. 1991). SRIC is becoming an important component of the rapidly changing forest products economy of the Pacific Northwest (Miner 1990) where several companies have established large farms to produce poplar fiber.

Although current knowledge is sufficient to establish productive *Populus* plantations, significant questions remain concerning effects of spacing and genotype deployment on growth and yield. Most clones have been selected based on growth performance in small, monoclonal evaluation plots of a single spacing. Few data have been collected to evaluate or compare growth and yield of clones in larger plots or in plots of different spacings. One European study has shown that relative growth of clones may differ by spacing (Panetsos 1980), but the experimental environment (i.e., different clones planted on adjacent spokes in a Nelder's design) consisted of interclonal as well as intraclonal competition. There is little information concerning the degree to which relative clonal performance in monoclonal planting changes with spacing. Several reviews have considered factors to be considered in decisions about clonal deployment (DeBell and Harrington 1993; Lindgren 1993; Zsuffa et al. 1993; Foster and Knowe 1995). In addition, diameter distributions have been modeled using data from several

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combinations of two clone mixtures of eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.) (Knowe et al. 1994), but there is a paucity of experimental data related to monoclonal versus polyclonal plantings. Preliminary reports exist for a small test in Yugoslavia (Markovi and Herpka 1986) and one in Oregon (R. Shuren. 1994 and 1996. Clonal deployment study at the Lower Columbia River Fiber Forest. James River Corporation, Camas, Wash., personal communication). Several questions must be resolved if poplar growers are to optimize deployment of selected clones. Do clones grow similarly (in absolute terms and relative to each other) in monoclonal and polyclonal blocks? Are there differences in yield between monoclonal and polyclonal blocks? Do the answers to these questions concerning deployment differ with spacing?

To help answer the above questions, we established monoclonal and polyclonal plantings of four *Populus* clones at three spacings. This paper reports 3-year results for survival, height, diameter, tree form, stand uniformity, and yield as affected by spacing in monoclonal and polyclonal plots.

Materials and methods

Site description

The research plantings for our study were established in spring 1990 at the Washington State Department of Natural Resources (DNR) Meridian Seed Orchard, located 12 km east of Olympia, WA. Elevation is about 50 m. Climate is mild with an average growing season of 190 frost-free days and a mean July temperature of 16°C. Precipitation averages 130 cm·year^{-1}, falling mostly as rain from October through May; summers are periodically dry. Prior to installation of this study, the immediate area was in native forest occupied by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and several hardwood tree and shrub species. The trees were felled, merchantable stems removed, stumps pushed out of the ground, and the nonmerchantable material burned in piles. The topography is level and is occupied by two distinct soil types, both derived from glacial outwash. Most of the area contains a very deep, somewhat excessively drained, loamy sand (soil series Indianola, classified as mixed, mesic Dystric Xeropsamment). A minor portion of the area had gravel contents of 20–30% in the loamy sand surface soil, but does not drain as rapidly as the formerly mentioned soil type. Because of low rainfall during the growing season, neither soil would be considered suitable for commercial *Populus* plantations without irrigation.

The site was disked after harvest and burning, and a mix of N-P-K fertilizers was applied 1 month prior to planting to provide the equivalent of approximately 100 kg·ha^{-1} each of N, P, and K. In addition, 900 kg lime·ha^{-1} was applied as a mixture of limestone and dolomite. Between the second and third growing seasons, an additional 100 kg N·ha^{-1} was applied as ammonium nitrate. Both the preplant and subsequent fertilizer applications (including lime) were spread on the soil surface but not incorporated. Preplanting and postplanting herbicide applications and hoeing were used as necessary to maintain the plots in a weed-free condition. Irrigation was provided by drip lines laid down 2 m apart; emitters (2.3 L·h^{-1}) were spaced at 1-m intervals along each line. Amounts of water applied varied by year and weather conditions, ranging from 75 to 100 cm·ha^{-1}·year^{-1}.

Experimental design and treatments

The study was established as a factorial design with five clonal treatments (four clones planted in monoclonal plots and one polyclonal plot with all clones in intimate mixture) and three square spacings, replicated in three blocks.

The four *Populus* clones were selected for use based on availability of stock, contrasting branching characteristics, and superior growth. Three of the clones were *P. trichocarpa* Torr. & Gray × *P. deltoides* Bartr. ex Marsh. hybrids developed in the University of Washington – Washington State University poplar breeding program (Heilman and Stettler 1985; Quinsey et al. 1991). The three hybrid clones were 11-11, 47-174, and 49-177, and they are currently used in many commercial plantations. Clone 11-11 is one of the first hybrids developed in the program, and it has been planted extensively throughout the Northwest; it grows rapidly and produces many sylleptic branches (i.e., branches that develop and elongate during the same growing season in which the bud is formed). Clone 47-174 grows very rapidly but produces very few sylleptic branches. Clone 49-177 grows very rapidly and produces many sylleptic branches. The fourth clone is a local selection of *P. trichocarpa* named Capitol Lake (CL) that had demonstrated excellent growth in small research plantings. It produces many sylleptic branches. Planting stock (unrooted cuttings) for the hybrids was provided by the James River Corporation; stock for the local *P. trichocarpa* clone was grown in the DNR nursery near Olympia.

The three square spacings (0.5, 1.0, and 1.5 m) were selected to provide a range of stand density conditions; the two wider spacings have been commonly used in research plantings and in operational bioenergy plantations. The narrowest spacing (0.5 m) provided a treatment in which competition developed more rapidly and to a higher degree.

Plot installation

Plot size varied by spacing; each treatment plot consisted of a 100-tree interior measurement plot (10 rows by 10 columns) surrounded by three to eight buffer rows. Areas where debris piles had been burned were delineated and excluded from use in the study. Two blocks of plots were located on the major soil type; the third block was placed on the gravelly, less rapidly draining soil type.

The plots were established with unrooted woody cuttings that were ≥1 cm in diameter, 30 cm long, and had several healthy buds present. Cuttings were soaked in water overnight and then firmed into holes created with metal rods. The goal was to insert approximately 25 cm of the cutting length into the ground, but two healthy axillary buds were to remain above ground. Previous experience indicated that establishment success (i.e., survival and early growth) was poor if cuttings did not have at least one healthy bud above ground (Radwan et al. 1987). Requiring two buds above ground ensured that a high percentage of cuttings sprouted but necessitated a later pruning to remove secondary or multiple stems. Planting was done during the last week of March 1990; stem pruning was done in autumn 1990.

Polyclonal plots were planted with 49-177 and CL alternating in even-numbered rows and 11-11 and 47-174 alternating in odd-numbered rows. Thus, the eight trees surrounding any individual subject tree represented a consistent composition of three clones, all of which differed from the subject tree.

Data collection and analyses

In both monoclonal and polyclonal plots, the 100-tree interior plot was used to measure tree dimensions and estimate standing biomass at the end of the third growing season. Tree diameter and height were recorded, and any unusual conditions (stem characteristics, stress or damage due to weather, insects, or diseases) were noted. Tree diameters were measured at 0.3 and 1.3 m above ground with metal diameter tapes and were recorded to the nearest 0.1 cm. Heights were measured with telescoping fiberglass poles and recorded to the nearest 5 cm.

Indices for lower-stem taper (0.3 m diameter/diameter at breast height (DBH) × 100) and slenderness (height/DBH × 100) were calculated from measurements of diameter and height. Coefficients of variation for diameter and height were calculated for each 100-tree measurement plot, and the three plot values were averaged to provide a mean coefficient of variation for each treatment.

To estimate standing biomass at age 3, five trees were selected

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Table 1. Results of ANOVA for various tree and stand characteristics.

Tree characteristics						
	Source of variation					
Trait	C	S	D	C×S	C×D	C×S×D
Survival	**	**	0.18	**	0.07	*
Height	**	**	**	**	**	**
DBH	**	**	**	**	**	0.09
Lower-stem taper	**	**	**	**	**	**
Slenderness	**	**	0.07	**	**	**
Branch index	*	**	na	*	na	na
Live and dead branches	**	**	na	0.59	na	na
Live branches	**	**	na	0.28	na	na
1992 sylleptic branches	**	**	na	0.10	na	na

Stand characteristics			
	Source of variation		
Trait	S	CT	S×CT
Stem yield	**	**	0.93
Branch yield	**	**	0.09
Total woody yield	**	**	0.90
Coefficient of variation			
Height	**	**	0.12
DBH	**	**	0.51

Note: C, clone; S, spacing; D, deployment; CT, clonal treatment. **Significant at $P < 0.01$; *significant at $P < 0.05$; actual values shown for $P > 0.05$; na, not analyzed because specific data collected only in monoclonal plantings.

Table 2. Survival of *Populus* clones at the end of the third growing season by clone, spacing, and type of deployment.

	Survival by clone (%)			
Block type	11-11	47-174	49-177	CL
	0.5-m spacing			
Monoclonal	94 *a*	94 *a*	81 *a*	82 *a*
Polyclonal	97 *a*	92 *a*	88 *a*	43 *b*
	1.0-m spacing			
Monoclonal	100 *a*	98 *a*	91 *a*	100 *a*
Polyclonal	100 *a*	99 *a*	88 *a*	99 *a*
	1.5-m spacing			
Monoclonal	100 *a*	100 *a*	91 *a*	100 *a*
Polyclonal	100 *a*	96 *a*	93 *a*	99 *a*

Note: Means followed by the same letter do not differ significantly at $P = 0.05$.

Table 3. Mean height and diameter at age 3 by type of clonal deployment, clone, and spacing.

	Height (m)		DBH (cm)	
Clone	Monoclonal	Polyclonal	Monoclonal	Polyclonal
	0.5-m spacing			
11-11	6.7 *i*	7.0 *i*	3.2 *j*	3.4 *ij*
47-174	6.9 *i*	6.6 *i*	3.2 *j*	3.1 *j*
49-177	6.9 *i*	7.8 *h*	3.5 *ij*	4.2 *i*
CL	6.6 *i*	3.9 *j*	3.2 *j*	1.5 *k*
Mean	6.8	6.3	3.3	3.2
	1.0-m spacing			
11-11	9.9 *e–g*	10.3 *b–f*	5.7 *gh*	6.0 *f–h*
47-174	10.0 *d–g*	9.9 *e–g*	5.6 *h*	5.4 *h*
49-177	9.8 *e–g*	10.9 *a–d*	5.9 *gh*	6.9 *d–f*
CL	9.2 *g*	6.6 *i*	5.2 *h*	3.2 *j*
Mean	9.7	9.4	5.6	5.4
	1.5-m spacing			
11-11	11.0 *a–c*	11.2 *ab*	7.6 *b–d*	8.3 *ab*
47-174	11.0 *a–c*	10.3 *c–f*	7.4 *b–e*	6.6 *e–g*
49-177	11.3 *a*	11.2 *a*	8.0 *a–c*	8.9 *a*
CL	10.6 *a–e*	9.5 *fg*	7.0 *c–e*	5.6 *gh*
Mean	11.0	10.6	7.5	7.3

Note: Within a column, means followed by the same letter do not differ significantly at $P = 0.05$.

Tree form

Lower-stem taper and slenderness differed among clones and spacings, and these traits differed in some clones and some spacings between monoclonal and polyclonal plots (Table 4). At age 3, clone 11-11 had the least taper; its taper did not change significantly with spacing and did not differ in monoclonal versus polyclonal plantings. Clone 47-174 had the greatest lower-stem taper in monoclonal plots and differed significantly from other clones at the two widest spacings, but its taper did not differ between polyclonal and monoclonal plantings. The taper of clones 49-177 and CL tended to be intermediate between the other two clones. Taper of clone CL did not differ significantly with spacing in monoclonal plots, but it decreased with increased spacing in polyclonal plots. Moreover, the taper of clone CL was significantly greater in polyclonal than in monoclonal plantings at the two closest spacings. Taper of clone 49-177 was unaffected by either spacing or deployment.

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Table 5. Coefficients of variation (%) in height and diameter at age 3 for *Populus* clones in monoclonal and polyclonal plantings at three spacings.

	Clonal treatment					
Spacing	11-11	47-174	49-177	CL	Polyclonal	Mean*
			Height			
0.5 m	30.9	25.7	28.1	24.4	31.4	28.1 *A*
1.0 m	14.8	12.5	18.1	11.0	22.1	15.7 *B*
1.5 m	6.8	9.3	13.9	8.1	12.4	10.1 *C*
Mean†	17.5 *bc*	15.8 *c*	20.0 *ab*	14.5 *c*	22.0 *a*	
			DBH			
0.5 m	36.4	32.7	34.0	32.5	41.2	35.3 *X*
1.0 m	20.2	17.2	21.8	17.2	30.8	21.4 *Y*
1.5 m	12.3	15.8	18.3	13.4	24.4	16.8 *Z*
Mean†	22.9 *b*	21.9 *b*	24.7 *b*	21.0 *b*	32.1 *a*	

*Within this column, spacing means followed by the same letter do not differ significantly at $P = 0.05$.

†Within this row, clonal treatment means followed by the same letter do not differ significantly at $P = 0.05$.

variation for diameters in the 1.0- and 1.5-m polyclonal plots were more than 60% higher than the mean of coefficients of variation for the corresponding monoclonal plots whereas they were only 22% higher at the 0.5-m spacing. Similarly, polyclonal plantings had coefficients of variation for diameter that were 33–41% higher than those for the most variable clone (49-177) in monoclonal blocks at 1.0- and 1.5-m spacing and only 13% higher than the most variable monoclonal plantings (11-11) at 0.5-m spacing. In general, trends for variation in height are similar (although less striking) to those for variation in diameter.

Stand yield at age 3

Aboveground yields differed significantly among clones and spacings (Tables 1 and 6). Three-year total live woody yields ranged from a low of 35.2 Mg·ha^{-1} for clone CL at 1.5-m spacing to a high of 54.9 Mg·ha^{-1} for clone 49-177 at 0.5-m spacing. Averaged over all spacings, total live woody yields at age 3 in monoclonal plantings were 48.7 Mg·ha^{-1} for 49-177, 45.9 Mg·ha^{-1} for 11-11, 45.3 Mg·ha^{-1} for 47-174, and 37.3 Mg·ha^{-1} for CL. Total woody yields of polyclonal plots (43.1 Mg·ha^{-1}) were significantly higher than yields from monoclonal plots of CL.

Total woody yields of all clonal treatments decreased as spacing increased, with yield at 1.5-m spacing being significantly lower than yields at the two closer spacings. Stem yield patterns were similar to patterns for total live woody yields as they constituted more than 90% of total yield (Table 6). Branch yield, however, increased with increased spacing, and was significantly greater at 1.5-m spacing than at the other two spacings. Clonal rankings in branch yield also differed from rankings in stem and total woody yield; overall, clone 49-177 had significantly higher branch yield than the other three clones in monoclonal plots. At the widest spacing, however, branch yields of clones 47-174 and CL were slightly higher than those of clone 49-177, a striking reversal of the clonal rankings of branch yield at the 0.5-m spacing and presumably was associated with greater longevity of lower branches in clones 47-174 and CL at this spacing.

Both stem and total woody yield of polyclonal plots tended to be slightly lower than those of the average of monoclonal plots but not significantly so (Fig. 1; Table 6). Averaged over all clones and spacings, monoclonal plots yielded live woody biomass of 44.3 Mg·ha^{-1} whereas polyclonal plots yielded 43.1 Mg·ha^{-1}. There were substantial differences, however, between monoclonal and polyclonal deployment in the contribution of each clone to total yield (Fig. 1). Moreover, the magnitude of such differences varied by spacing. The clones made rather similar contributions (22–27%) to total yield in monoclonal plantings at the widest spacing (1.5 m). For polyclonal plantings at that spacing, clones 49-177 and 11-11 provided 35 and 31% of total yield, respectively, whereas clones 47-174 and CL provided only 20 and 14%. The disparity among clones in polyclonal plots was much greater as spacing decreased. At 0.5-m spacing, clone CL provided only 1% whereas clone 49-177 provided 46% of the total yield.

Table 6. Characteristics of aboveground, oven-dry stand yield in *Populus* plantings at 3 years.

	Yield (Mg·ha^{-1})		
Clonal treatment	Stem	Live branches	Total live woody
		0.5-m spacing	
Monoclonal			
11-11	47.4	2.5	49.9
47-174	47.2	2.3	49.5
49-177	51.2	3.7	54.9
CL	36.8	2.1	38.9
Mean	45.6	2.6	48.2
Polyclonal	44.2	2.8	47.0
Spacing mean	45.4 *A*	2.7 *B*	48.0 *A*
		1.0-m spacing	
Monoclonal			
11-11	45.6	2.6	48.2
47-174	43.5	2.8	46.3
49-177	44.7	3.6	48.3
CL	34.9	2.8	37.7
Mean	42.2	3.0	45.1
Polyclonal	41.5	2.9	44.4
Spacing mean	42.1 *A*	2.9 *B*	45.0 *A*
		1.5-m spacing	
Monoclonal			
11-11	36.2	3.2	39.4
47-174	35.5	4.6	40.1
49-177	38.8	4.3	43.1
CL	30.8	4.4	35.2
Mean	35.3	4.1	39.4
Polyclonal	33.7	4.2	37.9
Spacing mean	35.0 *B*	4.1 *A*	39.1 *B*
		All spacings	
Monoclonal			
11-11	43.1 *a*	2.8 *b*	45.9 *a*
47-174	42.0 *a*	3.2 *b*	45.3 *a*
49-177	44.9 *a*	3.9 *a*	48.7 *a*
CL	34.2 *b*	3.1 *b*	37.3 *b*
Mean	41.0 *a*	3.2 *b*	44.3 *a*
Polyclonal	39.8 *a*	3.3 *ab*	43.1 *a*

Note: Spacing means followed by the same uppercase letter and clonal means (all spacings) followed by the same lowercase letter do not differ significantly at $P = 0.05$.

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to the generality for some traits; for example, its yields in polyclonal and monoclonal plantings were more similar at 0.5- than at 1.5-m spacings. The latter reversal probably was related to the branching habit of 47-174; reduced sylleptic branching was not as great a disadvantage at close spacing where syllepticity of all clones was minimal. At the wider spacing, however, where syllepticity was fully expressed, clone 47-174 was at a much greater competitive disadvantage relative to other clones such as 11-11 and 49-177 which grew rapidly and produced many sylleptic branches.

Some people argue on theoretical grounds that yield in polyclonal plantings may be higher and that deployment in more diverse plantings may protect plantations from catastrophic losses by distributing risks more evenly on the landscape. Our study failed to show any yield advantage of polyclonal plantings. Monoclonal yields of some individual clones exceeded polyclonal yields, but not significantly so, and yield of one clone (CL) was significantly lower. Moreover, on average, polyclonal yields were slightly (although not significantly) lower than the four-clone average of monoclonal yields. Hazards that may hinder tree survival and growth are many as are the mechanisms through which they enter, affect, and spread through a plantation. Such differences in damaging agents are obviously important considerations in deployment strategies. Other things being equal, however, the theoretical risk-spreading advantages may be less than one might otherwise assume if relative yield of individual clones changes markedly in polyclonal plantings. In 0.5-m spacings, for example, 46% of inventory was tied up in just one clone (49-177) and another 29% in a second clone (11-11); the remaining two clones accounted for only 25% of inventory. When the same four clones were deployed in monoclonal plantings, however, their relative contributions to overall production and inventory were much more similar, ranging from 20% for clone CL to 28% for clone 49-177. In our plantings, risks were spread over a less balanced inventory — in effect, relying on a less diverse population — when the same four clones were deployed in polyclonal plantings than in monoclonal plantings. Although this effect might be reduced with inclusion of additional or different clones, the same principle would apply. It therefore seems important to understand and consider the effect of deployment strategies on the distribution and balance of inventory among clones.

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