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Production of hybrid poplar under short-term, intensive culture in Western Colorado

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ABSTRACT

An irrigated study was conducted at the Western Colorado Research Center at Fruita for 6 years to evaluate eight hybrid poplar clones under short-term, intensive culture. The eight clones included in the study were *Populus nigra x P. maximowiczii* (NM6), *P. trichocarpa x P. deltoides* (52225, OP367), and *P. deltoides x P. nigra* (Norway, Noreaster, Raverdaus, 14274, 14272). Data were collected for growth, aerial biomass yield, dry matter partitioning, carbon sequestration, and insect and disease infestation. OP367 and 52225 consistently had larger tree diameters than other hybrids for each of the 6 years. Averaged across clones, yield was 58.4 Mg ha^{-1}. OP367 had the highest yield at 72.2 Mg ha^{-1} and 14274 had the lowest yield at 41.0 Mg ha^{-1}. The yield of OP367 was 1.8 times greater than that of 14274. Carbon yield over the 6 years of testing was highest for OP367 at 33.4 Mg C ha^{-1} and lowest for 14274 at 18.8 Mg C ha^{-1}. Of the eight clones tested, OP367 was the most adapted and productive clone in this short-term, intensive culture system in the arid environment of the Grand Valley of western Colorado as evidenced by its productive growth, yield, insect resistance, winterhardiness, and tree architecture. Several insect species infested the poplar clones over the course of the rotation. Best management practices for growers who produce hybrid poplar under short-term, intensive culture should include the following: (1) plant highly productive clones, (2) poplar clones with suitable tree architecture for production and market objectives should be used, (3) if carbon sequestration is an important production objective, plant a suitable clone, (4) some poplar clones develop chlorosis when planted in high pH soils and should be avoided, and (5) use poplar clones that have been shown to exhibit resistance to specific insect species.

1. Introduction

Short-term, intensive culture of woody crop species was first considered 30 years ago as a rapid means to produce feedstock for fiber and energy applications (Tuskan, 1998). Production of hybrid poplar (*Populus* spp.) was initiated on large-scale, short-term intensive culture in the 1990s on farmland where agronomic crops have traditionally been produced (Eaton, 2000). Production practices for short-term, intensive rotations with hybrid poplar typically have high plant densities of approximately 1700 trees ha^{-1} when production cycles are completed in less than 8 years (Johnson, 2000). Hybrid poplar when grown under intensive, short-term culture conditions require best management production practices similar to many perennial crops, including considerations for plant spacing, cultivation, fertilization, irrigation, insect control, weed control, and other widely used agronomic production practices. Hybrid poplar produced under short-term, intensive culture can be considered an agronomic crop (Rice, 2000).

Hybrid poplar is produced for a number of uses including pulp, dimension lumber, oriented strand board, plywood, as well as conservation and ornamental plantings (Heilman et al., 1995). Hybrid poplar has also shown potential use in phytoremediation applications (Asare and Madison, 2000; Pilon-Smits et al., 1998). Wildlife can benefit from the habitats created by hybrid poplar plantations (Sage, 1998; Allen, 2000). Hybrid poplar plantations can affect avian and small mammal abundance and species richness, creating both positive and negative impacts (Christian et al., 1997). Growers experience negative impacts when animals cause tree damage at an economic level and wildlife experience negative impacts given the short-term rotation and the direct effect harvesting poplars can have on animals and their habitats.

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As a wood product, hybrid poplar can be used as a fuel source; however, recent efforts have focused on hybrid poplar as a renewable feedstock for energy to replace fossil fuels (Tolbert and Schiller, 1996). As a renewable feedstock for short rotation, hybrid poplar can also be coppiced to produce another crop. Because hybrid poplar is a fast-growing productive species, it may be a desirable source of cellulose for biofuels. In many situations, hybrid poplar can be grown on land areas and in cropping systems that would not compete for cropland used for traditional crops. For example, hybrid poplar could be grown by small or part-time landowners in irregular-shaped fields or on less productive, marginal land that is not suited for efficient production of many agronomic crops.

A wide selection of clones is commercially available and they have been shown to differ in various growth and performance characteristics and a diversity of uses (Ceulemans et al., 1996; Friend et al., 2000; Gochis and Cuenca, 2000; Moser, 2000). To promote economic profitability for growers, the highest yielding and adapted clones must be identified for specific crop production systems. The objective of this research was to evaluate hybrid poplar under irrigation in short-term, intensive culture as an agronomic crop in the arid environment of western Colorado. Data were collected for eight hybrid poplar clones for growth, aerial biomass yield, dry matter partitioning, carbon sequestration, and insect and disease infestation.

2. Methods and materials

2.1. Plant material and plot layout

A study was initiated at the Western Colorado Research Center at Fruita in 2000 to evaluate hybrid poplar under short-term, intensive culture conditions. The experiment was a randomized, complete block with four replications. A common recommendation for hybrid poplar is to provide 1 m^2 for each year the tree is in production; thus, for a 6-year production cycle, each tree would require a growing area of approximately 6 m^2. Each plot consisted of 36 trees arranged in a 6 by 6 tree configuration with each tree planted on a 2.44 m × 2.44 m spacing, totaling 214 m^2 per plot. One row of the clone Noreaster surrounded the entire experiment site. The eight hybrid poplar clones included in the study represented a diversity of genetic material with potential adaptation to western Colorado conditions (Table 1).

2.2. Field plot management

Hybrid poplars were furrow-irrigated using gated pipe. Irrigation water was from the Colorado River delivered through a canal system. Trees received regular irrigations during each growing season and water was not a limiting factor for production at any time throughout the duration of the study. The soil was a Billings silty clay loam (fine-silty, mixed, mesic Typic Torrifluvent) with a pH of 7.5–8.0. The seedbed was prepared by moldboard plowing in fall 1999. In spring 2000, the field was tilled using an S-tine harrow and culti-packer (roller harrow). The field was marked in perpendicular directions on a 2.44 m × 2.44 m spacing using a tractor and toolbar mounted with a furrow opener. The intersection of the marks designated where the trees were to be planted.

Planting occurred on 13 April 2000. Hybrid poplars were planted using 25-cm cuttings. A dibble stick was used to make 12.7 mm diameter holes into the soil. The hole was approximately 0.3 m deep. The cutting was inserted into the hole leaving the uppermost bud of the cutting just above the soil surface with little or no air pocket at the bottom of the hole. During planting we observed that the diameters of cuttings within and among clones varied somewhat, but in other research, cutting diameter was not found to be factor of major importance (Robison and Raffa, 1996). On the same day as planting, oxyfluorfen [2-chloro-1-(3-ethoxy-4-nitrophenoxy)-4-(trifluoromethyl)benzene] herbicide was applied at a rate of 1.12 kg active ingredient ha^{-1} in 205 L of water ha^{-1} at 138 kPa. Care was taken not to apply herbicide onto the cuttings. During the 2000 growing season the field was cultivated 3 times using a Lely Roterra power harrow (Model RH-200-20, Temple, TX).[4] Hand weeding was done twice during summer 2000 to remove weeds that were growing too close to the trees to use equipment or herbicides.

Glyphosate herbicide [*N*-(phosphonomethyl)glycine], at approximately 20 g kg^{-1} solution, was applied twice each year during 2000 and 2001 using a backpack sprayer to control summer weed flushes. A similar application of glyphosate was applied once in 2003 to control weeds. In other years, weeds were not a significant problem and were not competitive against poplars.

Ammonium nitrate was hand-applied at a rate of 112 kg N ha^{-1} each year using the rate suggested by Hansen (1993). The fertilizer was placed in the furrow next to each tree. Irrigation furrows were reshaped each year as needed using Acra-Plant trash tillers (Acra-Plant, Hutchinson, KS) and a small tractor that fit between tree rows.

2.3. Data collection

Bud break of each clone was determined in the spring of each year. Bud break was recorded when green tissue was visually apparent between bud scales on 50% or more of trees. Bud break was expressed in day of year.

During 2004, leaves on approximately the top fourth of the trees of NM6 were chlorotic. A 0.75 m section of a symptomatic, secondary branch with leaves was sampled randomly from one tree in each plot of the affected clone. Other clones were sampled similarly. Leaves were removed from the branch, air dried, and ground in a Wiley Mill (Standard Model no. 3, Arthur H. Thomas Co., Philadelphia, PA) using a 2-mm mesh screen. Leaf tissue was analyzed by the Colorado State University Soil, Plant, and Water Testing Laboratory for N, NO_3, P, K, Ca, Mg, Na, Fe, Mn, Cu, Zn, and B.

Of the 36 trees in each plot, the interior 16 trees (4 by 4 spacing arrangement) were used for data collection. Mortality was determined at approximately 45 days from planting when it was evident that the cuttings were dead and were not producing new growth. Each of the 16 cuttings in each plot was evaluated for mortality. To maintain uniform tree populations in each plot, missing trees were replanted in mid-May 2000 using extra cuttings that had been stored under refrigerated conditions.

During the first 2 years of growth, tree height was measured from the soil surface to the top of the tree (leaves not included) using a surveyor's measuring rod in the late fall 2000 and 2001 once leaf drop had occurred. After the first 2 years of growth, the trees were too tall and too close together to measure accurately. Trunk diameters were measured each year during late fall after leaves had fallen. Using a tree caliper, data for trunk diameter were collected at a 1 m height.

During August 2005, a randomly selected tree from each plot was harvested by cutting the tree at ground level with a chainsaw. Trees were partitioned into leaves, branches, and trunk. Plant partitioning data are reported as fresh weights. Wood moisture content was determined by cutting a small disc, approximately 6-cm thick, from the trunk. The disc was weighed immediately following harvest and oven-dried at 60 °C until a constant weight was obtained.

[4] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or their institutions.

Table 1
Description of the eight hybrid poplar clones used in short-term, intensive culture at the Western Colorado Research Center at Fruita, Colorado.

Hybrid poplar clone	Parentage	Notes
NM6	*Populus nigra x P. maximowiczii*	This clone is considered to be fast-growing but is sensitive to pH's greater than 7.5.
52225	*P. trichocarpa x P. deltoides*	This is a non-dormant hybrid and thus cold tolerance may be a problem in some temperate environments.
OP367	*P. deltoides x P. nigra*	A widely grown hybrid used in the northwest. It was developed in Maine.
Norway	*P. deltoides x P. nigra*	An older male hybrid that is common in the Great Plains area. Norway is considered to be an industry standard. It is moderately fast-growing, resistant to canker, and has good pH tolerance.
Noreaster	*P. deltoides x P. nigra*	A sterile female that is common in the Great Plains and is considered to have good disease resistance. It was developed at the University of Nebraska and released in 1979.
Raverdeau	*P. deltoides x P. nigra*	Considered to be one of the fastest-growing Euramericana hybrids and has good pH tolerance.
14274	*P. deltoides x P. nigra*	A 'newer' Euramericana hybrid developed at the Morden Experimental Station, Manitoba.
14272	*P. deltoides x P. nigra*	Also known as 'Prairie Sky,' and also from the Morden Experimental Station. This hybrid is single trunked, has good drought tolerance, and has fairly good disease resistance.

Hybrid poplar was monitored each growing season for insect pests. Pheromone traps for poplar twig borer, *Paranthrene tabaniformis* (Rottemburg), and western poplar clearwing, *Paranthrene robiniae* (Hy. Edwards), were set in 2002 and checked weekly. All pest insects were collected and identified to species. Specimens are stored in the Tri-River Area Extension Insect Collection in Grand Junction, CO. On 7 December 2005, the incidence of carpenterworm [Lepidoptera: Cossidae: *Prionoxystus robiniae* (Peck)] damage was determined by counting the exit holes along the bottom 1.5-m length of the trunk. The interior 16 trees in each plot were evaluated.

Poplars were harvested during the winter months in late December 2005 and early January 2006. The 16 interior trees of each plot were harvested using chainsaws. Trees were harvested and weighed individually. Trees were felled and cut into sections and weighed on a platform that was attached by cables to a 900-kg capacity load cell. The load cell was suspended from a small crane mounted on a three-point hitch on the back of a tractor. Trees were cut flush with the soil surface and all aerial phytomass was weighed (trunk and branches). Leaves had abscised by the time trees were harvested during the winter months. A small disc, approximately 6-cm thick, was cut from the trunk and used to determine wood moisture. The disc was weighed immediately after harvest, oven-dried at 60 °C, and reweighed. Final harvest data are reported on a dry weight basis.

2.4. Carbon concentration analysis

Following moisture determination, the disc was sawed into two half circles and approximately a 5-mm thick slab was cut from one of the halves such that the slab was a cross-section of the diameter of the tree trunk. A subsample of the slab was obtained by sanding the cross-section with fine sandpaper to include the bark of the tree. The wood subsamples were oven-dried at 60 °C for 24 h prior to C and N analysis. Tree core samples were analyzed for C and N content using an Elementar vario Macro C-N analyzer (Elementar Americas, Inc., Mt. Laurel, NJ). The data obtained for carbon sequestration is for aerial branches and trunk only and does not include carbon produced by leaves and roots. Carbon budgeting of hybrid poplar has been conducted previously by others (Peichl et al., 2006) and was not within the scope of our research.

2.5. Statistical analysis

Data were subjected to analysis of variance using Analytical Software Statistix 9 program (Analytical Software, 2008) to determine treatment (clone) effects. All statistical comparisons were conducted at the 5% level of probability using least significant difference method for mean separation. Data of each year for tree diameter were analyzed separately and LSD values were calculated at $P = 0.05$.

3. Results

A summary of precipitation, mean maximum, mean minimum, and mean monthly temperature data from 2000 to 2005 at the Grand Junction national weather service station, which is located 16 km east from Fruita is presented in Table 2. The average length of the growing season at Fruita is 181 days calculated on a freezing temperature of −2.2 °C. Adequate irrigation water was available for hybrid poplars during the 6-year rotation cycle and water was not a limiting factor for hybrid poplar in any year.

Most clones established well with low mortalities (Table 3). Of the total number of trees measured in 2001, most clones had only one or two missing trees (Table 3). The exception to this was clone 14274 which had 20 trees missing or trees were so small they were not suitable for measurements.

Tree height produced during the first year of growth in 2000, averaged across all eight clones, was 2.47 m and, in 2001, the average height was 6.72 m (Table 3). Hybrid poplars grew approximately 2.5 m the first year and more than 4 m the second year. OP367 was the tallest clone the first year at a height of more than 3 m and the second tallest during the second year of growth at nearly 8 m. Clone 52225 was shorter than clone OP367 during the first year but during the second year there was no significant difference in tree heights between clones 52225 and OP367. Tree height of clone NM6 was 2.93 m and was not statistically significantly different in height from that of clone OP367 in the first year of growth. Tree heights of Norway, Noreaster, and Raverdeau were statistically

Table 2
Precipitation and temperature conditions from 2000 to 2005 at Grand Junction, which is located 16 km from Fruita.

Year	Mean maximum temperature (°C)	Mean minimum temperature (°C)	Mean temperature (°C)	Precipitation (mm)
2000	19.7	5.3	12.5	190.8
2001	19.7	5.2	12.4	213.4
2002	19.4	4.0	11.7	199.9
2003	19.9	5.3	12.6	185.7
2004	18.2	4.5	11.3	243.8
2005	19.4	4.8	12.1	300.2
30-year mean	18.4	3.6	11.0	228.3

Table 3
Tree mortality during the first (establishment) year of growth (2000) and tree heights of hybrid poplar during the initial 2 years of growth at Western Colorado Research Center at Fruita, Colorado.

Hybrid poplar cultivar	Mortality	2000 Tree height	2001 Tree height
	(%)	(m)	
NM6	2 a	2.93 ab	7.45 b
52225	2 a	2.88 b	8.08 a
OP367	0 a	3.13 a	7.90 a
Norway	2 a	2.38 c	6.35 c
Noreaster	0 a	2.28 cd	6.35 c
Raverdeau	3 a	2.30 cd	6.68 c
14274	31 c	1.80 e	5.18 e
14272	8 b	2.10 d	5.80 d
Average	6	2.47	6.72

Means within a column followed by a different letter are significantly different at the 5% level of probability.

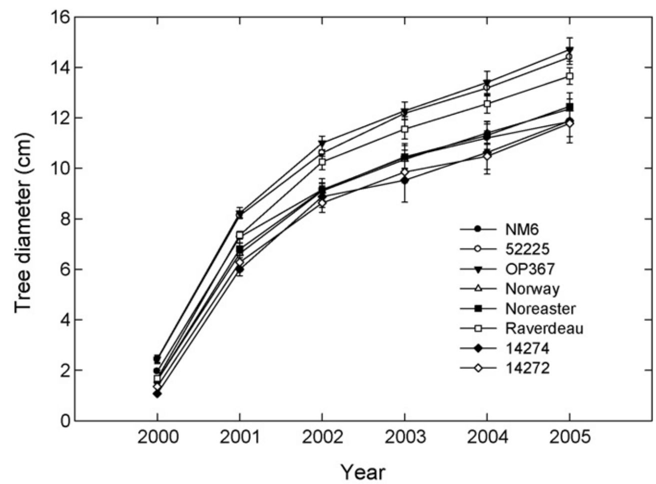

Fig. 1. Tree diameter at a 1 m height of eight hybrid poplar clones grown for 6 years from 2000 to 2005 at Fruita, CO. Each data point shows the standard error and the data point is the average of 4 replicates with up to 16 subsamples (trees) within each replicate.

similar, but were shorter than OP367 and NM6. During the first 2 years of growth, the shortest clones were 14274 and 14272.

Bud break was determined for each clone as an indicator of dormancy and winterhardiness (Table 4). Because there was a significant poplar hybrid by year interaction, data of each year for bud break were analyzed separately. In four of the 5 years, NM6 was the first clone to break dormancy. Clone 52225 was also among the first hybrids to break dormancy. Neither of these clones was very dormant. In all 5 years, Clone OP367 was the last hybrid to break dormancy. The difference between the first and last poplar hybrids to break dormancy varied depending on the year. The least difference was approximately 5 days in 2004 and the greatest difference was 22 days in 2001. Averaged across the 5 years, the difference between the first and last poplar hybrids to break dormancy was slightly more than 16 days.

Chlorosis was observed in the upper portion of the trees of clone NM6 during the 2004 growing season. Leaf tissue from all clones was analyzed (Table 5). Macro- and micronutrient content was determined. Only those elements that exhibited a significant response ($P \leq 0.05$) among poplar hybrids are presented in Table 5. Clones NM6 and 14272 showed the most consistent response. Leaf tissue analysis of NM6 revealed that N, Ca, Mg, and Mn were lower than that of most other hybrids. Leaf tissue analysis of clone 14272 revealed that Ca, Mg, Zn, and B were higher than that of most other hybrids.

The August 2005 sampling revealed that tree weights varied significantly among the poplar hybrids (Table 6). Averaged across all poplar hybrids, total tree fresh weight was 95 kg tree^{-1}. OP367 produced the heaviest tree at 130 kg and NM6 had the lightest tree weight at 53 kg, respectively. There was no significant differences in average tree weights among clones OP367, Raverdeau, 52225, and Norway. Wood moisture contents at late summer varied significantly among the poplar hybrids (Table 6). Averaged across all clones, wood moisture content at late summer was 49.4%. Clone 52225 had the highest moisture content at 54.8% while 14272 had the lowest moisture contents at 46.9%.

Leaf weight was highest for Raverdeau and OP367 and lowest for NM6. For branch weight, the highest yielding clone was OP367 and the lowest yielding clones were NM6 and 14274. Other clones were intermediate in yields for branch weight. Trunk weight was highest for OP367, 52225, Raverdeau, and Norway and lowest for NM6. In spite of the tree size produced by each clone, the partitioning of plant matter among branches and trunk was similar for the poplar hybrids, except one. Clone 52225 partitioned less of its plant matter into branches and more into its trunk. The percentage of plant matter that was partitioned into leaves by the clones ranged from 9 to 14% of the total plant matter.

Trunk diameter was measured at a 1 m height. Overall, trunk growth at a 1 m height was greatest during the second and third years of growth with an increase of slightly more than 5.3 cm in Year 2 and slightly more than 2.5 cm in Year 3 (Fig. 1). In other years, tree diameters at a meter height increased by 0.9–1.8 cm per year.

OP367 and 52225 consistently had larger tree diameters than other hybrids for each of the 6 years (Fig. 1). Raverdeau also had larger tree diameters in most years compared to other hybrids. Clones 14272 and 14274 consistently had small tree diameters compared to other hybrids over the 6-year production period. During the beginning of the rotation, NM6 had a trunk diame-

Table 4
Days from first of year when hybrid poplar began growth (bud break) each spring in a short-term, intensive culture from 2000 to 2005 at the Western Colorado Research Center at Fruita, Colorado.

Hybrid poplar cultivar	2001	2002	2003	2004	2005	Ave.
	days					
NM6	84.3 f	92.3 f	91.3 e	83.3 c	91.3 f	88.1
52225	93.0 e	98.3 e	95.0 d	79.3 d	98.0 e	92.5
OP367	106.0 a	104.8 a	109.0 a	88.5 a	111.0 a	103.9
Norway	100.8 c	102.5 bc	103.8 b	88.5 a	105.0 b	100.0
Noreaster	102.0 b	102.8 b	103.5 b	88.0 a	105.3 b	100.3
Raverdeau	102.5 b	101.3 cd	103.0 b	88.5 a	105.3 b	100.2
14274	92.5 e	100.8 d	101.8 c	83.5 bc	102.3 d	95.8
14272	98.3 d	101.5 cd	101.0 c	84.3 b	103.0 c	97.4
Average	97.4	100.5	101.0	85.5	102.6	97.3

Means within a column followed by a different letter are significantly different at the 5% level of probability.

Table 5
Elemental composition of leaf tissue of eight hybrid poplar cultivars in 2004 after 5 years of growth at Fruita, Colorado.

Hybrid poplar cultivar	N	Ca	Mg	Mn	Zn	B
	(%)			(mg kg^{-1})		
NM6	1.97 b	1.87 d	0.38 c	33 c	6.4 bcd	76 bcd
52225	1.89 b	2.42 ab	0.39 bc	61 bc	3.9 d	55 d
OP367	2.63 a	2.22 abcd	0.48 ab	85 abc	4.0 cd	61 cd
Norway	2.41 a	2.15 bcd	0.45 abc	82 abc	8.7 abcd	84 abcd
Noreaster	2.70 a	1.97 cd	0.42 abc	81 abc	9.9 abcd	91 abcd
Raverdeau	2.46 a	2.31 abc	0.46 abc	106 ab	10.2 abc	96 abc
14274	2.54 a	2.15 bcd	0.38 c	138 a	11.2 ab	105 ab
14272	2.56 a	2.62 a	0.51 a	118 ab	14.4 a	121 a
Average	2.40	2.21	0.43	88	8.6	86

Means within a column followed by a different letter are significantly different at the 5% level of probability.

Table 6
Aerial partitioning and wood moisture content of 6-year-old hybrid poplars grown at Fruita, Colorado. Sampling occurred during late summer 2005.

Hybrid poplar cultivar[a]	Leaf weight	Branch weight	Trunk weight	Total tree weight	Wood moisture content
	(kg tree^{-1})				(%)
NM6	6 (10) c	14 (27)[b] d	33 (63) d	53 d	50.0 bc
52225	10 (9) bc	17 (14) bcd	89 (77) ab	116 ab	54.8 a
OP367	14 (11) ab	26 (20) a	90 (69) a	130 a	52.0 ab
Norway	11 (12) b	22 (23) abc	65 (65) abc	98 abc	48.4 c
Noreaster	10 (12) bc	19 (21) abcd	61 (67) bcd	90 bcd	47.0 c
Raverdeau	16 (14) a	24 (20) ab	79 (66) abc	119 ab	47.4 c
14274	10 (14) bc	14 (20) d	51 (66) cd	75 cd	48.6 bc
14272	9 (13) bc	15 (19) cd	52 (68) cd	76 cd	46.9 c
Average	11 (12)	19 (20)	65 (68)	95	49.4

Means within a column followed by a different letter are significantly different at the 5% level of probability.
[a] One tree per clone was sampled in each of the four replications ($n=4$). Data reported are fresh weights.
[b] Percentages are shown in parenthesis—% leaves + % branches + % trunk = 100%.

ter that was slightly smaller than OP367 and 52225, but by the end of the rotation, trunk diameter of NM6 was among the smallest of the hybrids. Other clones were intermediate in their trunk diameters.

Wood moisture contents at harvest varied significantly among the poplar hybrids (Table 7). Averaged across all clones, wood moisture content at harvest was 50.0%. Clone 52225 had the highest moisture content at 54.8% while clone 14272 had the lowest moisture at 46.7%. Moisture contents at harvest for these hybrids were very similar to those obtained during the late summer sampling.

Individual tree dry weights at harvest varied significantly among the poplar hybrids (Table 7). Averaged across all poplar hybrids, tree weight was 34.7 kg tree^{-1}. Clone OP367 produced the largest tree at 43.0 kg tree^{-1} and 14274 had the lowest tree weight at 24.0 kg tree^{-1}, an 80% difference in average tree weight. Both OP367 and Raverdeau produced large trees while 14272 and 14274 produced small trees.

Poplar wood yield varied significantly among the clones (Table 7). Averaged across all clones, yield was 58.4 Mg ha^{-1}. Clone OP367 had the highest yield at 72.2 Mg ha^{-1} and 14274 had the lowest yield at 41.0 Mg ha^{-1}. Yields of other poplar hybrids were intermediate. The yield of OP367 was 75% higher than that of 14274. Yields of OP367 and Raverdeau were not significantly different.

Poplar clones differed significantly in N concentration, C concentration, C:N ratio, tree carbon content, and aerial C production (Table 8). Nitrogen concentration of the wood was highest for clones 14274 and 14272 and lowest for clones 52225 and OP367. Carbon concentration of the wood was highest for NM6 and lowest for OP367 and 14274 with other clones being intermediate. The C:N ratio was highest for clones NM6, 52225, and OP367 and lowest for 14274 and 14272. The average C content per tree was 16.3 kg tree^{-1} and the average aerial C production was 27.4 Mg ha^{-1}. On a per tree basis, the C content was highest for OP367 and Raverdeau and

Table 7
Wood moisture content, average single tree weight, and yield of hybrid poplar grown at Fruita, CO in a 6-year short-term, intensive culture rotation from 2000 to 2005.

Hybrid poplar cultivar	n	Wood moisture (%)	Single tree weight (kg tree^{-1})	Yield[a] (Mg ha^{-1})
NM6	64	48.3 d	31.9 bc	53.6 bc
52225	62	54.8 a	35.7 b	59.9 b
OP367	64	50.3 bc	43.0 a	72.2 a
Norway	64	50.7 b	35.8 b	60.1 b
Noreaster	64	51.5 b	35.8 b	60.1 b
Raverdeau	64	49.1 cd	40.4 a	67.9 a
14274	59	48.5 d	24.0 d	41.0 d
14272	61	46.7 e	31.1 c	52.3 c
Average		50.0	34.7	58.4

Means within a column followed by a different letter are significantly different at the 5% level of probability.
[a] Yields are reported on a dry matter basis.

Table 8
Nitrogen and carbon concentrations, C:N ratio, C content, and C production of hybrid poplar grown at Fruita, CO in a 6-year short-term, intensive culture rotation from 2000 to 2005 (Harvested December 2005–January 2006).

Hybrid poplar cultivar	*n*	Nitrogen ($g\,kg^{-1}$)	Carbon ($g\,kg^{-1}$)	C:N ratio	C content[a] ($kg\,tree^{-1}$)	Aerial C production[a] ($Mg\,ha^{-1}$)
NM6	64	1.76 cd	471 a	307 a	15.0 cd	25.2 cd
52225	61	1.67 cd	470 ab	306 a	17.0 b	28.6 b
OP367	63	1.54 d	464 c	309 a	19.9 a	33.4 a
Norway	63	2.19 b	469 ab	244 c	16.8 bc	28.3 bc
Noreaster	63	1.80 cd	470 ab	268 b	16.9 b	28.4 b
Raverdeau	62	1.92 bc	468 b	274 b	19.1 a	32.1 a
14274	57	2.88 a	465 c	187 d	11.2 e	18.8 e
14272	60	2.82 a	469 b	204 d	14.4 d	24.3 d
Average		2.07	468	262	16.3	27.4

Means within a column followed by a different letter are significantly different at the 5% level of probability.
[a] Carbon content and aerial C production was calculated on a dry matter basis.

lowest for 14274. On an area basis, the response of aerial C production for the clones was similar to the per tree C content. Carbon yield was highest for OP367 at 33.4 $Mg\,ha^{-1}$ and lowest for 14274 at 18.8 $Mg\,ha^{-1}$.

Borer damage by carpenterworms was first observed in the poplars during 2004. The only poplar hybrid found to have borer damage was clone 52225. No borer damage was found on any trees of other hybrids. The number of borer exit holes in 52225 ranged from none on some trees to a high as 40 holes on another tree. The number of exit holes for 52225 when averaged across the four replications was 13.1 ± 9.9 ($n = 61$) holes per tree. It is not clear if this is preferential feeding by the carpenterworms or actual susceptibility of 52225 to this particular insect. Regardless, 52225 is vulnerable to this insect species and should be avoided in preference to other more productive clones.

Cottonwood leaf beetle, *Chrysomela scripta* (F.), was a serious insect pest in this study. This insect first appeared in low numbers in 2001. Beetles were observed in significant numbers on 12 April 2002, when many adults were observed feeding and laying eggs on newly emerged leaves. The beetles were concentrated on clones NM6 and 52225, which had flushed leaves before other hybrids. A decision was made at that time to treat the entire planting with insecticide to eliminate any differential early season damage from cottonwood leaf beetle caused by concentration of beetles on the early flushing clones. Egg mass density has been found to be the most useful indicator for determining economic injury levels (Fang and Hart, 2000) and the economic injury level on 2-year-old poplar trees was found to range from 0.2 to 0.9 egg masses per growing terminal (Fang et al., 2002).

Two-spotted spider mites [*Tetranychus urticae* (Koch)] were abundant on the lower portion of the trees during August 2001. The populations were reduced by beneficial predators. Fall webworm, *Hyphantria cunea* (Drury), was present during late summer. This defoliator is highly conspicuous due to its large silken nest, but does little actual damage to the trees. Parasitism of larvae by beneficial wasps and flies typically reduces the population of fall webworm.

A total of 10 western poplar clearwing moths was captured in pheromone traps in July 2000 and on one date in September 2002. The peak flight appeared to be in July. No clearwing larvae were found in the trees. Four poplar twig borer moths were captured in mid- to late-July. Borers have the potential to become one of the more serious pests of poplar plantings during short-term, intensive culture of hybrid poplar.

Aphids (Homoptera: Aphididae) were found in isolated colonies during July, August, and September in most years. Aphids were kept in check by a significant population of beneficial insects, which included lady bird beetles (Coleoptera: Coccinellidae), syrphid fly larvae (Diptera: Syrphidae) and parasitic wasps (Hymenoptera: Braconidae). No clone preference feeding data were collected for aphids or associated beneficial insects.

4. Discussion

Tree architecture is an important factor for many commercial applications of hybrid poplar. For example, as saw logs and for manufacturing oriented strand board, trees of hybrid poplar need to be straight and columnar with minimal branching. Clones that have wavy (MN6, 52225) and twisted trunks are more difficult to debark and saw into dimension lumber. Clones that were erect and uniformly columnar were OP367 and somewhat less so for Raverdeau, 14274, and 14272. Basal branching was observed on clones 52225, 14274, and 14272. Norway and Noreaster had many large branches and a sprawling architecture.

Of the eight clones evaluated in this study, OP367 was overall the most superior clone tested. OP367 exhibited several superior characteristics. It exhibited superior growth during the first year that carried on throughout the additional 5 years of testing. Clone OP367 was the last hybrid to break dormancy each year of the testing period and accordingly should have good winterhardiness for our local conditions and other similar locations. Unlike NM6, OP367 did not develop any chlorosis and appeared well adapted to the alkaline soils of western Colorado.

OP367 had one of the largest tree diameters and produced the largest tree. Biomass partitioning of leaves, branches, and trunk of OP367 was similar to other clones. Nitrogen concentration was among the lowest, and the C:N ratio was among the highest, as was C concentration, and thus, C yield of OP367. Clone 52225 exhibited good growth parameters but it is non-dormant and could be susceptible to frost damage in some years. Furthermore, it was the only clone that experienced considerable damage by carpenterworms. Thus, OP367 was clearly the most adapted and productive clone in this short-term, intensive culture system in the arid environment of the Grand Valley of western Colorado as evidenced by its productive growth, yield, insect resistance, winterhardiness, and tree architecture. Several clones had some desirable characteristics, and some clones were not productive and had one or more unacceptable characteristics for the arid environment and high pH soils of western Colorado.

With minimal fertilization under rainfed conditions, Deckmyn et al. (2004) achieved simulated yields of up to 12.4 $Mg\,ha^{-1}\,year^{-1}$ using their crop model, and they postulated with irrigation and optimum N fertilization hybrid poplar yields could reach up to 22.4 $Mg\,ha^{-1}\,year^{-1}$. In our study, which included irrigation and optimum N fertilization, the most productive clone yielded 12.0 $Mg\,ha^{-1}\,year^{-1}$. The insect pressure from the cottonwood leaf beetles that occurred during the second year of production may have had a negative impact on yield that could have caused a yield reduction such that the poplars could not catch up, resulting in a lower overall yield response.

In the past, hybrid poplar has been grown for a variety of uses and more recently hybrid poplar has been promoted as a source of biofuel and for use to sequester C. Various plant species, including hybrid poplar, have been evaluated for their potential to sequester C, but little data are available on how poplar clones differ in the ability to sequester C. Peichl et al. (2006) found that above-ground tree components for 13-year-old hybrid poplar in southern Ontario, Canada sequestered 15.1 Mg C ha^{-1} when grown at a density of 111 trees ha^{-1}. In our 6-year hybrid poplar study, OP367, the clone with the highest aerial C production, sequestered 33.4 Mg C ha^{-1}. The tree density used in our study was 1681 trees ha^{-1}. Our data are for C production of trunk and branches, and does not include C for leaves and roots. In the work by Peichl et al. (2006), they found that leaves of hybrid poplar contributed approximately 10% to total aerial C and that 85% of the total tree C was stored in aerial biomass with the remaining 15% being stored in roots. Even without the C contribution from leaves and roots in our study, short-term intensive culture production of hybrid poplar has potential to sequester considerably more C than traditional hybrid poplar production systems. Carbon production among the clones in our study ranged from 18.8 t ha^{-1} for 14274 to 33.4 Mg ha^{-1} for OP367, a difference of 14.6 Mg ha^{-1}. Thus, the most productive poplar clone in our study increased C sequestration by as much as 90% compared to the least productive clone. Lal et al. (1998) used a net C assimilation rate of 5 Mg ha^{-1} $year^{-1}$ in their calculations when growing short-rotation woody crops and other energy crops. Their assumption of 5 Mg ha^{-1} $year^{-1}$ is similar to what we found for some of the hybrid poplar clones grown in western Colorado.

The cost to produce hybrid poplars under short-term, intensive culture in an arid environment under irrigation is an important factor that would affect the profitability of this production system. Irrigation water costs and availability vary considerably from location to location and should be evaluated when considering the production of hybrid poplar. The economics of short-term, intensive culture of hybrid poplar is important to aid producers in assessing the viability of commercial production. The findings from our study should be of value to economists in developing crop enterprise budgets for hybrid poplar grown under short-term, intensive culture.

Best management practices for growers who produce hybrid poplar under short-term, intensive culture should include the following: (1) poplar clones differ in their productivity and highly productive clones must be identified and planted that are adapted to local conditions, (2) poplar clones differ in their tree architecture and this can have a significant effect on production and market objectives, (3) poplar clones sequester different amounts of C, thus, if C sequestration is a production objective, suitable clones should be selected for planting, (4) some poplar clones may develop chlorosis when planted in high pH soils and they should be avoided, and (5) insects and diseases must be monitored regularly and controlled to avoid yield losses. Some poplar clones such as 52225 appear to be susceptible to some insect species. Growers should plant poplar clones that have been shown to exhibit resistance to specific insect species. Planting more than one clone may be a useful production strategy to avoid a monoculture that could expose an entire production potential pests or environmental problems. Additional research appears warranted to identify other hybrid poplar clones that are well adapted to western Colorado and similar environments.

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References

Allen, M., 2000. Fiber Farming Produces Record Growth. Tree Farmer, March/April, pp.14–17.

Analytical Software, 2008. Analytical Software Statistix9: User's Manual. Analytical Software, Tallahassee, FL.

Asare, S., Madison, M., 2000. Use of hybrid poplars for phytoremediation and other environmental applications. In: Blatner, K., Johnson, J.D., Baumgartner, D.M. (Eds.), Hybrid Poplars in the Pacific Northwest: Culture, Commerce, and Capability. Washington State University Cooperative Extension, MISCO272, Pullman, Washington, pp. 21–24.

Christian, D.P., Collins, P.T., Hanowski, J.M., Niemi, G.J., 1997. Bird and small mammal use of short-rotation hybrid poplar plantations. J. Wildl. Manage. 61, 171–182.

Ceulemans, R., Shao, B.Y., Jiang, X.N., Kalina, J., 1996. First- and second-year aboveground growth and productivity of two *Populus* hybrids grown at ambient and elevated CO_2. Tree Physiol. 16, 61–68.

Deckmyn, G., Laureysens, I., Garcia, J., Muys, B., Ceulemans, R., 2004. Poplar growth and yield in short rotation coppice: model simulations using the process model SECRETS. Biomass Bioenergy 26, 221–227.

Eaton, J.A., 2000. Growing sticks into shareholder value: life as a poplar tree farmer. In: Blatner, K., Johnson, J.D., Baumgartner, D.M. (Eds.), Hybrid Poplars in the Pacific Northwest: Culture, Commerce, and Capability. Washington State University Cooperative Extension, MISCO272, Pullman, Washington, pp. 45–48.

Fang, Y., Hart, E.R., 2000. Effect of cottonwood leaf beetle (Coleoptera: Chrysomelidae) larval population levels on *Populus* terminal damage. Environ. Entomol. 29, 43–48.

Fang, Y., Pedigo, L.P., Colletti, J.P., Hart, E.R., 2002. Economic injury level for second-generation cottonwood leaf beetle (Coleoptera: Chrysomelidae) in two-year-old *Populus*. J. Econ. Entomol. 95, 313–316.

Friend, A.L., Mobley, J.A., Ryan, E.A., Bradshaw Jr., H.D., 2000. Root growth plasticity of hybrid poplar in response to soil nutrient gradients. J. Sustain. Forest. 10, 133–140.

Gochis, D.J., Cuenca, R.H., 2000. Plant water use and crop curves for hybrid poplars. J. Irrig. Drain. Eng. 126, 206–214.

Hansen, E.A., 1993. A Guide to Determining When to Fertilizer Hybrid Poplar Plantations. USDA/Forest Service, North Central Forest Experiment Station, Research Paper NC-319.

Heilman, P.E., Stettler, R.F., Hanley, D.P., Carkner, R.W., 1995 (revised). High Yield Hybrid Poplar Plantations in the Pacific Northwest. Pacific Northwest Regional Extension Bulletin, Washington, Oregon, Idaho (PNW 356).

Johnson, J.D., 2000. Hybrid poplar: an overview. In: Blatner, K., Johnson, J.D., Baumgartner, D.M. (Eds.), Hybrid Poplars in the Pacific Northwest: Culture, Commerce, and Capability. Washington State University Cooperative Extension, MISCO272, Pullman, Washington, pp. 15–19.

Lal, R., Kimble, J.M., Follett, R.F., Cole., C.V., 1998. The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Sleeping Bear Press, Inc., Chelsea, MI, pp. 52–54.

Moser, B.W., 2000. A comparison of physical, chemical, and genetic controls to reduce deer browse damage to hybrid poplar seedlings. In: Proceedings of the 19th Vertebr, Pest Conference, Univ. of Calif., Davis, 19, pp. 88–92.

Peichl, M., Thevathasan, N.V., Gordon, A.M., Huss, J., Abohassan, R.A., 2006. Carbon sequestration potentials in temperate tree-based intercropping systems, southern Ontario, Canada. Agroforest. Syst. 66, 243–257.

Pilon-Smits, E.A.H., de Souza, M.P., Lytle, C.M., Shang, C., Terry, N., 1998. Selenium volatilization and assimilation by hybrid poplar (*Populus tremula x alba*). J. Exp. Bot. 49, 1889–1892.

Rice, D.E., 2000. Fiber farm experiences—west of the Cascades. In: Blatner, K., Johnson, J.D., Baumgartner, D.M. (Eds.), Hybrid Poplars in the Pacific Northwest: Culture, Commerce, and Capability. Washington State University Cooperative Extension, MISCO272, Pullman, Washington, p. 43.

Robison, D.J., Raffa, K.F., 1996. Importance of cutting diameter and method of production on early growth of hybrid poplar. Tree Planters' Notes 47, 76–80.

Sage, R.B., 1998. Short rotation coppice for energy: toward ecological guidelines. Biomass Bioenergy 15, 39–47.

Tolbert, V.R., Schiller, A., 1996. Environmental enhancement using short-rotation woody crops and perennial grasses as alternatives to traditional agricultural crops. In: Lockeretz, W. (Ed.), Environmental Enhancement through Agriculture. Tufts Univ. Medford, MA, pp. 209–216.

Tuskan, G.A., 1998. Short-rotation woody crop supply systems in the United States: what do we know and what do we need to know? Biomass Bioenergy 14, 307–315.