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Early Clonal Survival and Growth of Poplars Grown on North Carolina Piedmont and Mountain Marginal Lands

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Abstract The western half of North Carolina has abundant marginal pasturelands that vary greatly in altitude. Studies have demonstrated high *Populus* productivity on coastal plains and eastern Piedmont regions. Our objective was to identify best-performing *Populus* clones on marginal pasturelands representing upper Piedmont (Salisbury, 215 m above sea level, m.a.s.l.), northern Blue Ridge Mountains (Laurel Springs, 975 m.a.s.l.), and southern Blue Ridge Mountains (Mills River, 630 m.a.s.l.). At Salisbury, height and basal diameter (BD) were significantly related to clones ($p < 0.0001$), and some clones were affected by clone-spacing interaction while spacing affected aboveground wood volume significantly ($p < 0.0001$). At Mills River, clonal survival ($p < 0.0011$), height, and volume ($p < 0.0051$) varied with contrasting significance of some clonal differences between spacings. At Laurel Springs, survival varied among clones in 1 m × 1 m spacing ($p = 0.003$) but not 2 m × 2 m spacing while heights and volumes differed in both spacings ($p < 0.0058$). Clone 185 was consistently in the top 10 % for height, BD, and survival at all sites and spacings while other clones performed variably. Height-BD regressions were affected by clones, spacing, and sites. Volume had no clear correlations with precipitation, photosynthetically active radiation, temperature, and altitude across sites while height correlated with precipitation. Our results compared favorably with published results in other US regions, and show short rotation poplars have efficacy in Piedmont and mountain regions if the right clones in terms of growth/productivity, survival, and disease resistance are selected. Larger clonal performance variations are expected as competition increases, and highlight importance of experimentally determining suitable clones for specific sites.

Keywords Bioenergy feedstock · Blue Ridge Mountains · Marginal lands · Genomic groups · Piedmont · Site adaptability

Introduction

The importance of woody biomass as a major bioenergy feedstock for future renewable energy production [1, 2] and the high productivity potential and the expected role of *Populus* in ensuring sustainable feedstock production have been recognized [3]. However, renewable energy policies such as the RFS2 regulations [4] and the European sustainability guidelines [5] may explicitly or implicitly discourage the use of more productive lands for bioenergy production [6, 7], highlighting the need for substantial non-contentious land for bioenergy production. As a result, the use of marginal lands for bioenergy production is necessary [8].

The western half of North Carolina has abundant pasture or fallow marginal lands, due to low fertility soils, slope and often degrading past land-use practices. Sites also differ greatly in altitude and aspect. Yet, much of the *Populus* research in the South has been on less variable sites than western North Carolina. *Populus* productivity is influenced by genotype-environment interactions [9], thus identifying clones suitable for specific areas and growing conditions is critical for successful short rotation *Populus* forestry [10]. It is important to

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evaluate productivity potential, survival, and disease resistance of *Populus* clones on Piedmont and the mountain regions of North Carolina where so much marginal land exists since adaptability of hybrid poplars to land marginality (unfavorable growing conditions) can be improved by heterosis [9], especially given a large number of poplar clones native to North Carolina (Eastern cottonwood), and their hybrids are commercially available[1] and have not been tested for these regions. Such research can have extensive regional relevance since the Piedmont physiographic province stretches from Pennsylvania to Alabama and includes Virginia, South Carolina and Georgia, and the Blue Ridge mountain province includes Virginia, North Carolina, Tennessee, South Carolina, and Georgia.

In addition, most Christmas trees are grown on marginal lands; however, due to expanding markets, improved quality of artificial trees and overproduction of wholesale Christmas trees in North Carolina and Oregon, the value of Christmas trees has been impacted, forcing many farms to close leaving landowners a need for alternative income crops. Producing bioenergy feedstock offers landowners that own marginal lands possibilities of generating income and keeping their farms. Yet, sufficiency of the potential of marginal lands for sustainable bioenergy feedstock production is yet to be fully assessed [9, 11].

This paper reports first-year results on a study where the principal objective is to identify the best-performing young *Populus* clones at different planting densities on marginal pasturelands in the Piedmont and Blue Ridge Mountain physiographic regions of North Carolina, representing the Central Piedmont, the Northern Mountains, and the Southern Mountains climate divisions.

Materials and Methods

Non-irrigated trials were established at three research stations in western North Carolina (Fig. 1) representing physiography of 32 counties of North Carolina, and operated jointly by the North Carolina Department of Agriculture and Consumer Services and North Carolina State University: the Piedmont Research Station near Salisbury, the Mountain Horticultural Crops Research and Extension Center in Mills River, and the Upper Mountain Research Station in Laurel Springs. Details of the study sites, clones, and experimental design are provided in Tables 1, 2, and 3. Site preparation included herbicide applications and sub-soiling. Site management involved as-needed applications of herbicides (Table 1) to eliminate weeds and grasses growing along tree rows, and as-needed mowing between tree rows in order to minimize groundcover competition with trees while obtaining soil conservation benefits.

At the end of the 2014 growing season, all trees at the three sites were inventoried for survival, and tree heights of all living trees were measured using height poles (Crain CMR Series Measuring Rod, Crain Enterprises Inc., Memphis, TN, USA) while outside-bark basal stem diameters (BD) were measured using digital calipers (MyCal-Lite Series 700 Digital Calipers, Mitutoyo America, Chicago, IL USA) 0.15 m above the base of shoots formed off the sticks planted. Additional stems with significant growth formed from the sticks planted or within the bottom 0.15-m height of main stems were considered separate stems, and their heights and diameters were measured in the same manner as main stems. Productivity was estimated as the outside-bark aboveground wood volume, which hereafter is referred as wood volume or volume (m^3 ha^{-1}), using height, BD, and the equation by Shelton et al. [12] adjusted for use with BD, which entailed offsetting BD-based volumes of all trees for which BD and DBH were measured to match their DBH-based volumes and applying the offset to trees for which DBHs were not measured. For each clone or clone × spacing within a block, wood volume (m^3 ha^{-1}) was estimated as the ratio of total wood volume of trees to the area occupied by all (dead and living) trees, and survival (%) was calculated by dividing the number of living trees by the number of trees planted.

To determine if early growth, wood volume, and survival differed significantly ($\alpha = 0.05$) among clones and spacings, height, BD, volume, and survival data were analyzed using ANOVA [13] using Proc GLM since all levels of the factors of interest were measured. To examine which clones were affected by spacing, analysis of LS means for clone × spacing interactions (interaction effect) were partitioned by clones using analysis of simple effects [14] of SAS software known as SLICE statement [15]. In addition, regressions between height and BD of all clones were analyzed using Analysis of Covariance (Proc GLM) and Proc REG [13]. To examine effects of key site variables, heights, and wood volumes of clones in 2 m × 2 m spacing at the three sites were plotted against seasonal precipitation, incident photosynthetically active radiation (PAR) and growing degree days (GDD) and altitude (above sea level). GDD (°C) was calculated as the cumulative of mean air temperature above base temperature for plant growth [16], which was assumed 10 °C.

Results

At Salisbury (215 m a. s. l), clone, spacing, and interaction effects on survival were insignificant (Table 4). Clonal effects on survival at Mills River (630 m a. s. l.) were significant ($p < 0.0001$ to 0.0011), although there were contrasts between

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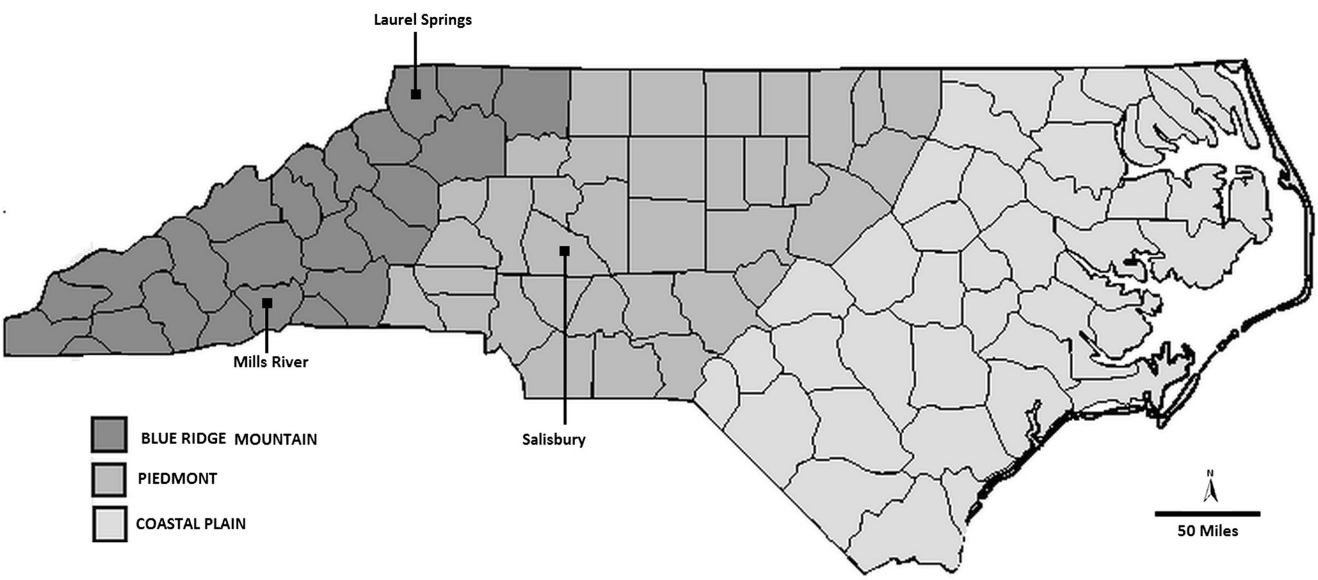


Fig. 1 A map of locations of the study sites and the physiographic classification of North Carolina

the trials on the significance of some clonal differences (Table 5). Full analyses of spacing and interaction effects on survival of clones common at the Orchard and Hill Slope were not performed since preliminary analyses showed that site differences were large enough to influence comparison. At Laurel Springs (975 m a. s. l.), clonal effects on survival were significant in 1 m × 1 m spacing ($p = 0.003$) but not 2 m × 2 m spacing (Table 5).

Height and BD at Salisbury were significantly affected by clone and interaction effects (Fig. 2, Table 4) although not all clones were affected by interaction effect. Clonal wood volumes were affected by interaction effect significantly ($p < 0.0001$ to 0.0482) and their rankings in the spacings were not the same. At Mills River, clonal differences in height, BD, and volume were significant although performances (volume and height) of some clones at Orchard and Hill Slope trials contrasted. There were significant clonal differences in multi-shoot formation ($p = 0.0055$), with clone 177 having more multi-shoot trees (17 %) than clones 185, 188, and 373 (single shoot) at the Orchard, while at the Hill Slope, clones 339, 373, 188, 302, and 5077 had more multi-shoot trees (13.3–20 %) than others. At Laurel Springs, height and BD

Table 1 Details of the study sites and the stands

Site/altitude (m.a.s.l.)	Physiography (Climate Division)	Precipitation annual/season[a]	PAR[b]/ GDD[c]	Planted	Soil texture Bulk density (g cm^{-3})	Spacing (Density, ha^{-1})	Weed Management
Salisbury/215	Piedmont (Central Piedmont)	1118 mm (676 mm)	3082/2233	March 2014	Loam 0.93–1.01	2 m × 1 m (5000) 2 m × 2 m (2500)	Banding: Segment ™,
Mills River/630	Blue Ridge Mountains (Southern Mountains)	1261 mm (953 mm)	2760/1762	April 2014	Loam 0.93–0.96	2 m × 2 m (2500)	Lontrel ®, MICROYL™
					Sandy clay loam 0.9–0.93	2 m × 1 m (5000)	Spot treatment: Gly Star® Pro -
Laurel Springs/975	Blue Ridge Mountains (Northern Mountains)	1244 mm (820 mm)	3196/1313	April 2014	Sandy clay loam 0.72–0.91	1 m × 1 m (10,000) 2 m × 2 m (2500)	Mowing

(Data source: State Climate Office of North Carolina)

m.a.s.l. meters above sea level

[a] Precipitation: season (source: State Climate Office of North Carolina)—total precipitation starting from a week before planting to the end of the October/season

[b] PAR (in μmol s^{-1} m^{-2}): photosynthetically active radiation (during growing season)—(data source: State Climate Office of North Carolina)

[c] GDD (°C): cumulative degree days for the growing season—based on mean air temperature measured at 2-m height above ground and base temperature of 10 °C

Table 2 Experimental designs and statistical models of the study sites

Site/	Experimental design	Additive models
Salisbury	Split-Plot:	$y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \gamma_k + \delta_{ik} + e_{ijk}$
	12 clones; 2 spacings; 16 replicates; 3 blocks	μ overall mean of the experiments
		α_i effect of treatment i
		β_j effect of treatment j
		$\alpha\beta_{ij}$ effect of treatment interactions
		γ_k effect of block k
		δ_{ik} block random error
		e_{ijk} sub-block random error
Mills River	Randomized complete block design:	$y_{ij} = \mu + \alpha_i + \beta_j + e_{ij}$
	• 16 clones; 3 replicates; 3 blocks	μ overall mean of the experiment
	• 10 clones; 10 replicates; 3 blocks	α_i effect of treatment i
		β_j effect of block j
		e_{ij} random error
Laurel Springs	Cluster randomized block design	$y_{ijk} = \mu + \alpha_i + \delta_j + \nu_{ij} + e_{ijk}$
	• 17 clones; 11 replicates; 6 blocks	μ overall mean of the experiment
	• 32 clones; 3 replicates; 3 blocks	α_i effect of treatment i
		δ_i effect of block j
		ν_{ij} random error at cluster level
		e_{ijk} random error component at subject level
Analysis of covariance (ANCOVA)		$y_{ijk} = \mu + \alpha_i + \beta(x_{ij} - \bar{x}.) + e_{ij}$
		μ overall true mean of the experiment
		α_i treatment effects with allowance for y-x relationship
		β common slope of the regression lines
		ν_{ij} overall mean of the covariate study subjects
		e_{ij} random error

significantly varied among clones (Table 4, Fig. 2 and Supplemental Fig. 1), but clones with the greatest height or BD did not necessarily have the greatest wood volume. Due to more trees with multiple shoots, clones DN-34 (33.5 %) and OP-367 (25.7 %) had the highest volumes in 1 m × 1 m spacing, and clones DN-34 (67 %) and 140 (58 %) in 2 m × 2 m spacing.

Site differences affected clonal survival and wood volume in 2 m × 1 m (Fig. 3a) and 2 m × 2 m (Fig. 3b) spacings, and adaptability (volume and survival) to particular sites varied

Table 3 Details of clones at the study sites and their genotypes

Site	Clones (Genomic groups)
Salisbury	140(DD), 176(DD), 177[a], 185(TD), 187(TD), 188(TD), 210[a], 229(TD), 302(TD), 312[a], 342(TD), 356(DD)
Mills River (2 m × 2 m)	140(DD), 174[a], 177[a], 185(TD), 187(TD), 188(TD), 210[a], 229(TD), 302(TD), 339(TD), 342(TD), 373(DD), 379(DD), 426[a], 455[a], 5077(TD)
Mills River (2 m × 1 m)	140(DD), 174[a], 177[a], 185(TD), 188(TD), 302(TD), 339(TD), 373(DD), 379(DD), 426[a]
Laurel Springs (1 m × 1 m)	176(DD), 185(TD), 187(TD), 188(TD), 210[a], 229(TD), 230(DM), 312[a], 339(TD), 342(TD), 356(DD), 373(DD), 379(DD), 419[a],426[a], 443[a], DN-34(DN), OP-367(DN)
Laurel Springs (2 m × 2 m)	129(TD), 140(DD), 174[a], 176(DD), 177[a], 185(TD), 187(TD), 188(TD), 198(DD), 200(DD), 210[a], 224(DD), 229(TD), 230(DM), 302(TD), 312[a], 339(TD), 340(TD), 341(TD), 342(TD), 356(DD), 373(DD), 379(DD), 400(DD), 419[a], 422[a], 426[a], 434(DD), 443[a], 455[a], 5077(TD), DN-34(DN)

[a] Clones of unknown genotypes

Genomic groups: **D** = *P. deltoides* Bartr. ex Marsh.; **T** = *P. trichocarpa* Torr. & Gray; **M** = *P. maximowiczii* A. Henry; **N** = *P. nigra* L

Table 4 Statistical results of clonal survival and growth (ANOVA) and height-BD regressions (ANCOVA)

	Site/trial	Effects	ANOVA P value (F value)				ANCOVA P value (F value)	
			Survival	Height	BD	Wood volume	Slope	Intercept
Salisbury:	Clone		0.0569(1.9)	<0.0001(39.2)	<0.0001(24.9)	0.0313(2.2)	<0.0001(6.3)	–
	Spacing		–	0.05505(0.4)	0.2587(1.3)	<0.0001(153.6)	0.37(0.8)	0.04(4.2)
	Clone × Spacing		0.8473(0.6)	0.0013(2.8)	<0.0001(3.8)	0.583(0.9)	–	–
Mills River:	Hill Slope	Clone	0.001(3.8)	0.0043(2.3)	0.0039(2.4)	0.0051(3.0)	<0.0001(6.8)	–
	Orchard	Clone	0.0011(5.5)	<0.0001(6.5)	<0.0001(9.9)	0.0036(4.4)	–	–
	Hill Slope vs. Orchard	Spacing	–	–	–	–	<0.0001(21.7)	–
Laurel Springs:	1 m × 1 m	Clone	0.003(2.5)	<0.0001(24.8)	<0.0001(24.4)	0.0003(3.1)	<0.0001(6.1)	–
	2 m × 2 m	Clone	0.013(1.9)	<0.0001(5.4)	<0.0001(4.5)	0.0058(2.1)	0.24(1.2)	<0.0001(3.1)
	1 m × 1 m vs. 2 m × 2 m	Spacing	–	–	–	–	0.17(1.9)	<0.0001(116.8)
Salisbury vs. Mills River		Site (2 m × 1 m)	–	–	–	–	<0.0001(38.4)	–
Salisbury vs. Mills River vs. Laurel Springs		Site (2 m × 2 m)	–	–	–	–	<0.0001(44.6)	–

among clones. Mean heights in 2 m × 2 m spacing were greater at sites with lower precipitation while seasonal PAR, seasonal GDD and altitude of the sites affected height inconsistently (Fig. 4). Wood volume had no clear relationships with precipitation, PAR, growing degree days, and altitude of the sites (Fig. 5) since most clones had mixed responses to the site variables although volume of some clones varied consistently with increasing amount of a particular variable. Clonal height-BD regressions varied significantly (*$p < 0.0001$*), and correlations (R^2) were higher at Laurel Springs (0.56–0.95) and Mills River (0.79–0.92) than Salisbury (0.37–0.80). Effects of spacing and site (the same spacing) on height-BD regressions were significant (Table 4).

Discussion

Dry wood biomass of 5–30 Mg ha^{-1} year^{-1} have been reported for 1- to 10-year-old hybrid poplars aged, in various regions of the USA [17–21 and references therein], and assuming dry wood density of *Populus* of 479.5 kg m^{-3} [22], is equivalent to wood volume of 0.011–0.062 m^3 ha^{-1} year^{-1}. Volumes of all clones at our three sites fell within the above range. Moreover, seven clones in 2 m × 1 m spacing at Salisbury (0.029–0.046 m^3 ha^{-1} year^{-1}), all clones at Mills River Orchard (0.038–0.049 m^3 ha^{-1} year^{-1}), and clone DN-34 at Laurel Springs in 2 m × 2 m spacing (0.014–0.038 m^3 ha^{-1} year^{-1}) were within the upper half of the range while all clones in 1 m × 1 m spacing had volumes higher than 0.069 m^3 ha^{-1} year^{-1}. Our results also compared favorably with productivities of irrigated multi-clonal poplar studies in western Colorado (0.02–0.024 m^3 ha^{-1} year^{-1}) and Washington State (0.019–0.037 m^3 ha^{-1} year^{-1}) involving various spacings [23–25]. Even without irrigation, tree heights at our sites compared well to heights from irrigated studies in western Colorado (1.8–3.13 m) [25], and Washington State (1.59–2.28 m) [23]. At Salisbury, clonal mean height was 1.8–3.14 m and mean heights of all clones at Mills River-Orchard (1.6–2.5 m) were better than first-year heights reported by DeBell and Harrington [23]. At Laurel Springs, all clones in 1 m × 1 m spacing but one, and half of the clones in 2 m × 2 m spacing had mean heights within the range of the abovementioned irrigated studies. Our findings are encouraging as they compared well with studies many of which were irrigated or not on marginal lands.

Variations in clonal effects and genomic groups among sites and the significance of identifying best clones on poplar productivity have been observed []. Other studies found interspecific hybrid poplars to be superior to intra-specific clones [17, 26 and references therein). Conversely, a study found height and diameter differences between different *Populus* taxa for short rotations to be insignificant, although the best performing interspecific clones were bigger than the best-performing intraspecific clones [21]. Our results showed that there were no particular advantages of height, volume, and survival resulting from interspecific versus intra-specific genotypes. At Salisbury for instance, interaction effects on height, BD, and volume occurred on clones with DD (*Populus deltoides–Populus deltoides*) and TD (*Populus. trichocarpa–Populus deltoides*) taxa. High performing clones at Mills River also included clones with DD and TD parents, while clones with relatively low survival (140, 373, and 379) had DD taxon. Top performing clones at the three sites were not necessarily the same, and effects of genomic grouping on how clonal performances differed among sites were inconsistent. For example, for TD taxon, Clones 187, 229, 302 and

Table 5 Statistical results of clonal survival (%) and wood volume (10^{-3} m^3 ha^{-1}) at Salisbury, Mills River, and Laurel Springs

Clone	Salisbury				Mills River				Laurel Springs			
	2 m × 1 m		2 m × 2 m		Orchard (2 m × 1 m)		Hill Slope (2 m × 2 m)		1 m × 1 m		(2 m × 2 m)	
	Survival	Volume	Survival	Volume	Survival	Volume	Survival	Volume	Survival	Volume	Survival	Volume
129	–	–		–	–	–	–	–	–	–	78 a	16.9 b
140	79 a	39.3 a	71 a	17.4 a	77 b	37.5 b	80 ab	20.1 ab	–	–	100 a	33.6 ab
174	–	–	–	–	93 ab	43.4 ab	93 a	20.1 ab	–	–	67 a	16.8 b
176	60 a	29.3 a	79 a	18.6 a	–	–	–	–	97 a	96 abc	89 a	19.2 ab
177	75 a	36.3 a	65 a	15 a	97 a	49.3 a	93 a	21.4 ab	–	–	67 a	16.7 b
185	96 a	43.5 a	96 a	23.4 a	100 a	44 ab	94 a	23 ab	97 a	94.9 abc	100 a	22.2 ab
187	98 a	45.8 a	85 a	18.8 a	–	–	100 a	22.9 ab	96 ab	88.7 abc	89 a	23.9 ab
188	77 a	33.7 a	94 a	20.4 a	100 a	43.7 ab	100 a	25.8 a	97 a	92.8 abc	100 a	24.2 ab
198	–	–	–	–	–	–	–	–	–	–	100 a	21.7 ab
200	–	–	–	–	–	–	–	–	–	–	100 a	24 ab
210	92 a	41.2 a	79 a	17.3 a	–	–	80 ab	20 ab	87 ab	83 abc	100 a	24.2 ab
224	–	–	–	–	–	–	–	–	–	–	100 a	24 ab
229	87.5 a	42.6 a	96 a	25.5 a	–	–	100 a	24.4 ab	93 ab	95.4 abc	100 a	26.5 ab
230	–	–	–	–	–	–	–	–	93 ab	91.7 abc	100 a	21.6 ab
302	98 a	44 a	92 a	20.2 a	100 a	48.2 ab	100 a	24.3 ab	–	–	100 a	26.6 ab
312	73 a	31.9 a	73 a	17.2 a	–	–	–	–	87 ab	85.4 abc	89 a	24 ab
339	–	–	–	–	97 a	46.9 ab	100 a	25.7 a	96 ab	90.8 abc	100 a	22 ab
340	–	–	–	–	–	–	–	–	–	–	100 a	26.5 ab
341	–	–	–	–	–	–	–	–	–	–	100 a	26.5 ab
342	96 a	42.8 a	94 a	25.9 a	–	–	87 ab	15.2 ab	100 a	102.8 ab	100 a	24.2 ab
356	75 a	33.6 a	83 a	18.3 a	–	–	–	–	73 b	68.5 c	56 a	14.3 b
373	–	–	–	–	87 ab	37.7 b	100 a	24.4 ab	93 ab	88.5 abc	89 a	23.8 ab
379	–	–	–	–	97 a	47.8 ab	80 ab	21.4 ab	85 ab	81.2 abc	89 a	26.3 ab
400	–	–	–	–	–	–	–	–	–	–	100 a	24.1 ab
419	–	–	–	–	–	–	–	–	85 ab	77.6 bc	56 a	14.5 b
422	–	–	–	–	–	–	–	–	–	–	78 a	16.7 b
426	–	–	–	–	83 ab	37.5 b	60 b	14.3 b	84 ab	78.8 bc	89 a	19.3 ab
434	–	–	–	–	–	–	–	–	–	–	100 a	23.9 ab
443	–	–	–	–	–	–	–	–	84 ab	76.4 bc	100 a	26.4 ab
455	–	–	–	–	–	–	80 ab	17.2 ab	–	–	56 a	16.7 b
5077	–	–	–	–	–	–	100 a	25.8 a	–	–	100 a	24.3 ab
DN–34	–	–	–	–	–	–	–	–	97 a	112 a	100 a	38 a
OP–367	–	–	–	–	–	–	–	–	100 a	108.9 ab	–	–
$MSD_{a=0.05}$	59.6	30.9	72.7	19.2	17.5	11.1	31.7	10.2	23.5	26.7	59.7	19.5
CV	24.2	27.1	29.4	32.9	6.4	8.7	11.5	15.3	12.4	32.7	20.4	26.3
SE	11.7	6.1	14.3	3.8	3.5	2.2	6.0	1.9	4.6	6.4	10.7	3.4

Means with the same letter within a column are not significantly different

Wood volume (10^{-3} m^3 ha^{-1}) and survival (%) are means values

MSD minimum significant difference, *SE* standard error

342 had greater volumes at Laurel Springs but volumes of clones 185, 187, 339, and 5077 were higher at Mill River (Fig. 3).

Fortier et al. [27] observed significant differences in biomass partitioning to stem, branches, and foliage among *Populus* clones. *Populus* and its clones generally employ one of two shoot production strategies: maintaining main stem(s) early on (*P. trichocarpa* and *P. trichocarpa* × *P. deltoides*) or maintaining multiple branching, which *Populus nigra* employs [9, 28, 29]. In our study, this was evidenced by

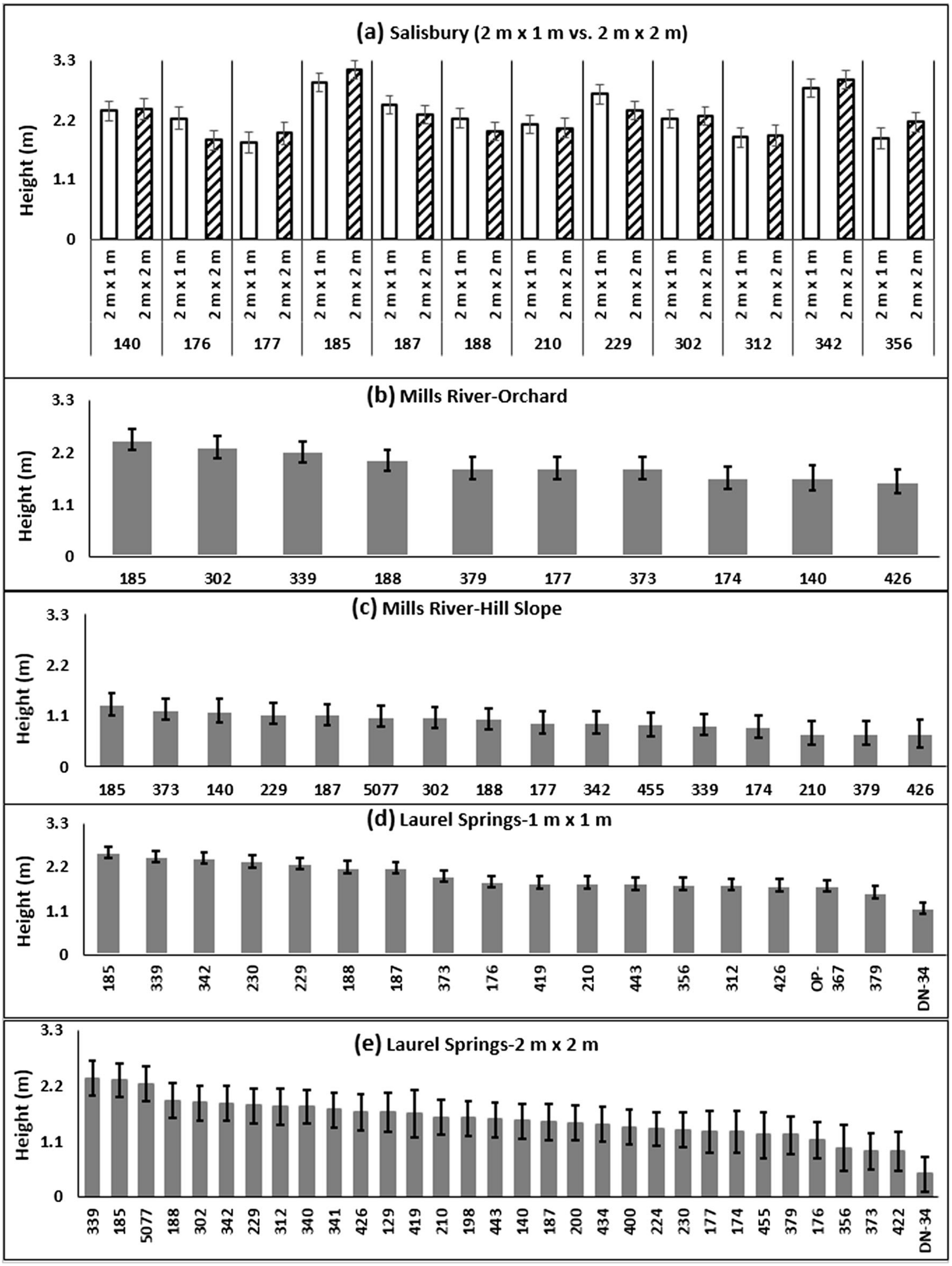


Fig. 2 Tree height (±2 standard errors) of clones at the study sites

significantly higher percentage of second shoot presence of clones DN-34 and OP-367, which are the only clones with *P. nigra* as a parent. Although multi-stemmed clones in our study had higher estimated outside-bark volumes, their inside-bark wood volumes may not necessarily be greater than or comparable to inside-bark volumes of single stemmed, since the trees with multiple smaller stems are likely to have higher proportions of bark. Effects of competition are expected to be more prominent as trees increase in size and with increasing number of shoots following harvests [9]. As a result, more

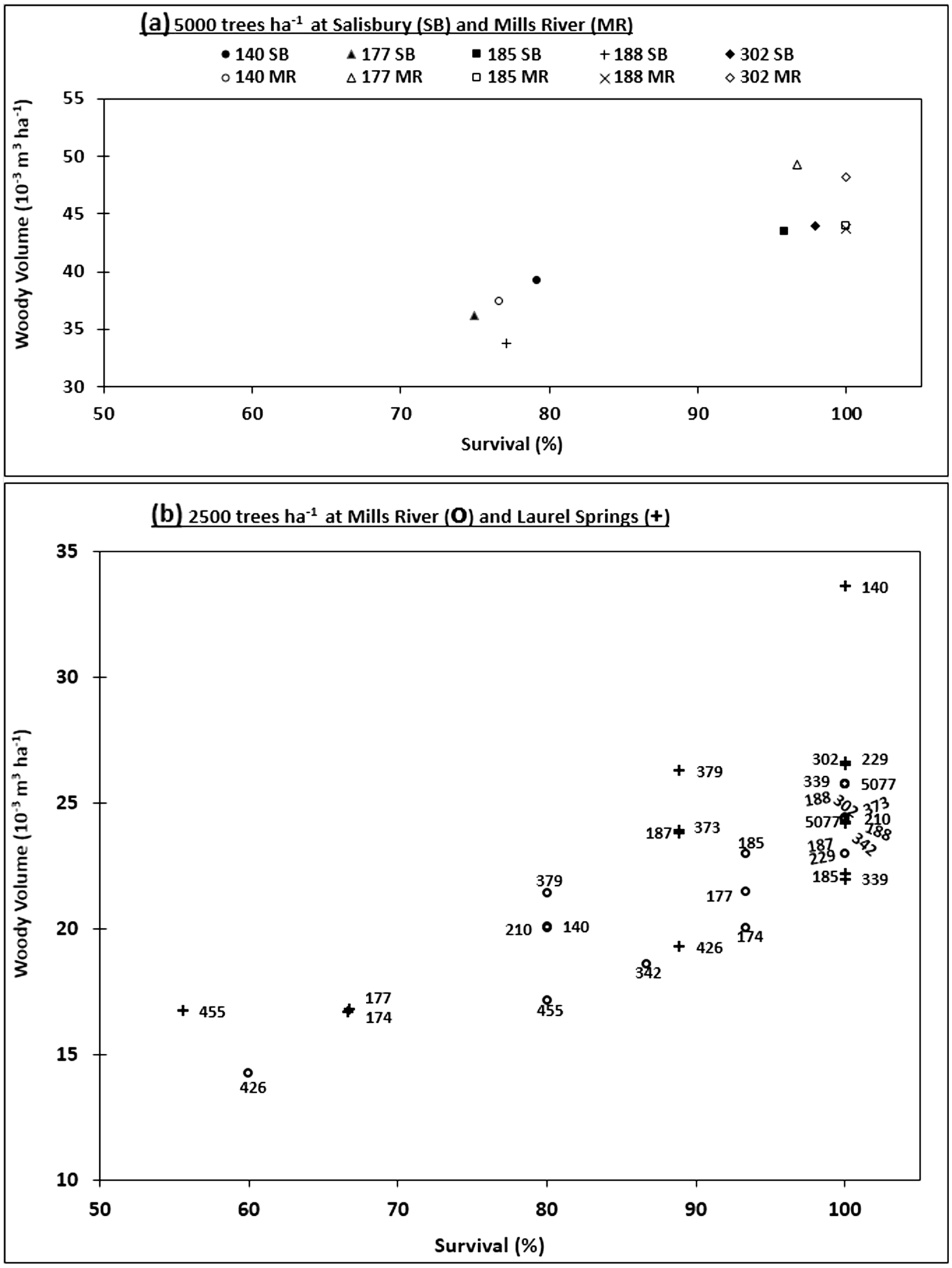


Fig. 3 Wood volume versus survival of clones in **a** 2 m × 1 m spacing (5000 trees ha^{-1}) at Mills River and Salisbury and **b** 2 m × 2 m spacing (2500 trees ha^{-1}) at Millis River and Laurel Springs

distinctions of growth, productivity, and survival among clones can be expected, attributed to differences in clonal adaptability during competition for light between shoots, which is also a function of density [30, 31] and photosynthesis efficiency [32].

Populus productivity is affected by site differences [18, 20]. Our results (Figs. 4 and 5) showed that clonal responses to site variables could not be clearly associated with genomic groups. It is worth mentioning that Laurel Springs had the shortest season, and there were frost incidents even after planting that killed the early buds, yet the site had comparable or higher precipitation and PAR but lower GDD versus the other sites. A study found temperature effects on productivity of short rotation *Populus* to be of low significance and highlighted wide adaptability of poplars [21]. Contradicting information have been reported about which of temperature and precipitation has a greater impact on poplar productivity [21 and references therein] and our results yielded no confirmation. For *Populus*, height has been correlated with main stem diameter [33], which helps to estimate productivity when only stem diameter is available [9, 34]. Such regressions vary from region to region due to genotype-environmental interactions

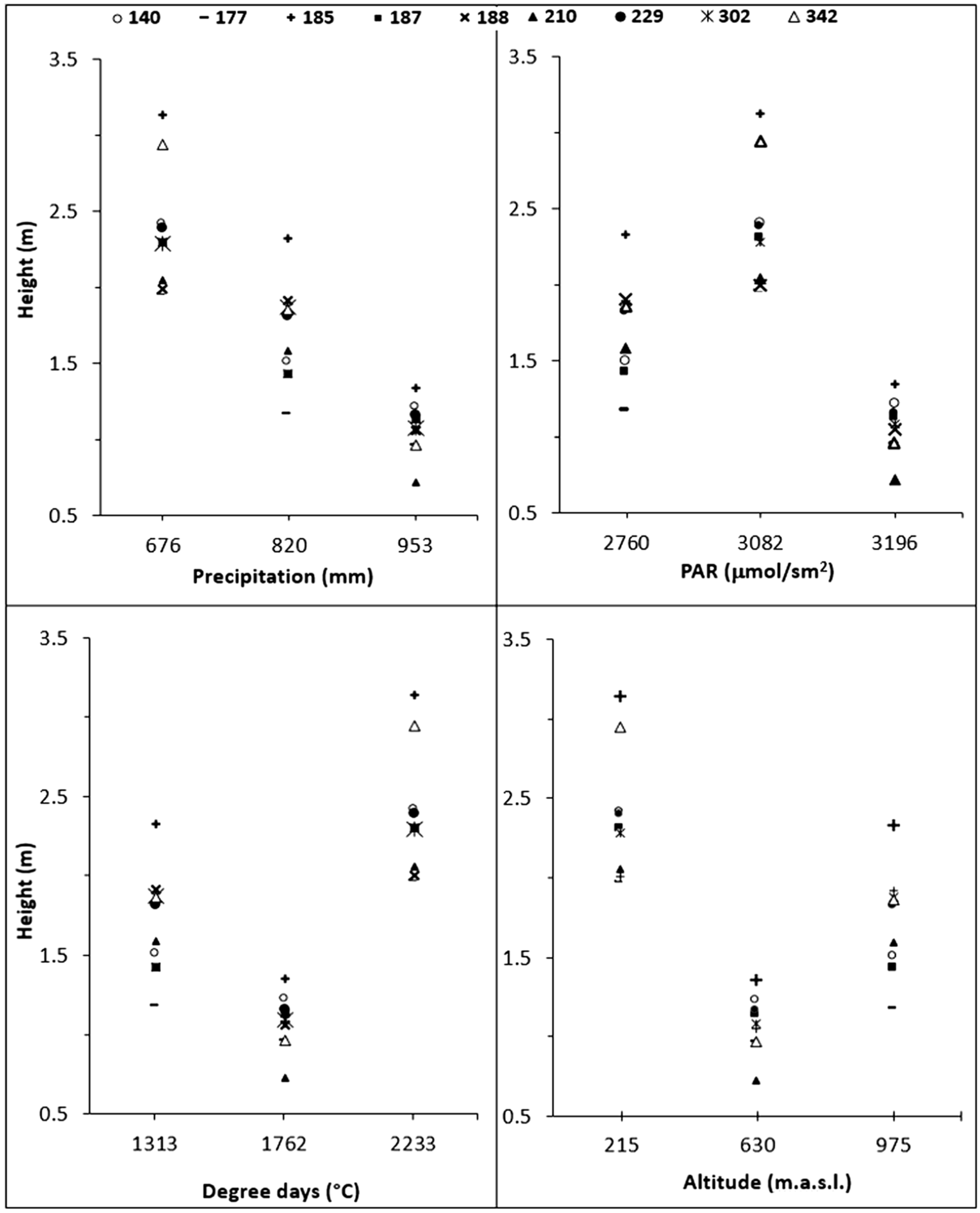


Fig. 4 Precipitation, PAR and growing degree days during the growing season, and altitudes of Salisbury, Millis River, and Laurel Springs versus tree height of clones in 2 m × 2 m spacing (2500 trees ha^{-1})

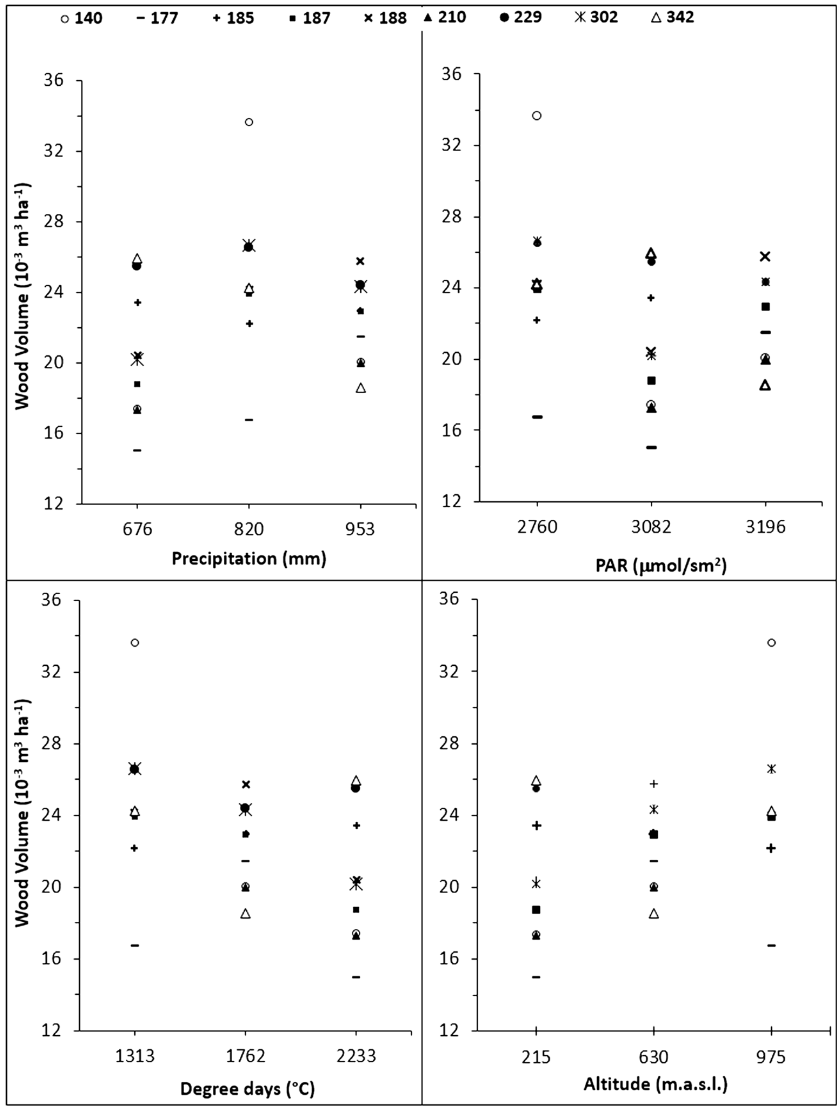
[35] and this was supported by our results. Our results highlight that while BD can sufficiently describe variations in height, such regressions vary among clones, spacing and sites, and regression equations developed for a clone should not be used for another clone without adjustment or evaluation.

There were no disease threats to wood of the poplar clones at the study sites during the study period, and leaf diseases that could hinder photosynthesis and growth did not occur during the active growing period of the growing season, although leaf rust caused by *Melampsora medusa* Thüm., occurred during early leaf senescence (towards the end of the season) with visible differences among clones. Hence, the selection of the right clones for bioenergy feedstock production at these regions should take into account clonal performance in terms of growth and productivity, survival, and resistance to diseases and pests.

Conclusion

Our objective was to assess early growth and survival of poplars as a potential energy feedstock for large amounts of marginal pasturelands in western North Carolina, especially considering the growing likelihood of a need to have income alternatives for the historic large wholesale Christmas industry in western North Carolina that is undergoing reductions in market demand. Our results show that at Salisbury (Piedmont), spacing and interactions significantly affected

Fig. 5 Precipitation, PAR and growing degree days during the growing season, and altitudes of Salisbury, Millis River, and Laurel Springs versus wood volume of clones in 2 m × 2 m spacing (2500 trees ha^{-1})



height, BD, and wood volume but not survival although not all clones were affected by interaction effect. At Mills River (southern North Carolina Mountains), clonal performances varied significantly, while significance of some clonal differences contrasted between Orchard and Hillslope. At Laurel Springs (northern Mountains), clonal survival varied significantly in 1 m × 1 m spacing but not 2 m × 2 m spacing, while height, BD, and volume significantly varied among clones in both spacings. Clone l85 was consistently in the top 10 % for height, BD, and survival for all three sites and spacings while performance of other clones varied among sites or spacings. Genomic groups had no clear relationships with volume, survival, adaptability to sites, and responses to precipitation, temperature, light, and altitude. Height-BD regressions were affected by clones, spacing, and sites. Heights and volumes of our top performing clones compare favorably with published results in the United States. Our results demonstrate that the efficacy of poplars as SRWCs for Piedmont and mountain regions is valid especially given that no disease threats to wood were present at the sites and that leaf diseases that could hinder photosynthesis and growth did not occur during active growing period of the season provided. Selection of the right clones for a particular regions should be based on clonal superiority in growth/productivity, survival, and resistance to diseases and pests. The large differences in clonal performance validates our supposition that it is critical to experimentally determine which clones are suitable for specific sites, and are expected to be more pronounced due to clones, density, sites, and their interactions as the trees grow and compete for resources more aggressively.

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