ORIGINAL PAPER

Survivorship, attained diameter, height and volume of three *Paulownia* species after 9 years in the southern Appalachians, USA

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Abstract Little is known of the tree and stand dynamics of varied species of planted *Paulownia* left unmanaged until harvest in the southeastern United States. We sought to remedy this lack of information needed by land managers to make informed decisions by investigating differences in survivorship, attained diameter breast height (DBH), diameter at ground level, total height, tree volume and stand-level volume yields of planted *P. elongata, P. fortunei,* and *P. tomentosa* in the cool-moist environment of the southern Appalachian Mountains. After 9 years, combined-species survivorship was only 27.3%. Low survivorship was likely related to several inclement weather events. *P. fortunei* was significantly smaller in DBH and total height. Three combined-species stem (bole) volume models were developed as functions of (1) DBH squared, (2) the product DBH squared and total height, and (3) the product diameter ground line squared and total height. Mean total volume production of unmanaged stands was greatest for *P. elongata* and *P. fortunei* 4 years after planting; by the 9th year, total volume of *P. elongata* was greater than the other two species. Results of our study provide managers information on productivity of three species of *Paulownia* that can be used for estimating plantation yields.

Keywords Diameter · Tree height · Stand structure · Stem volume · *Paulownia*

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Introduction

The genus *Paulownia* consists of nine species of deciduous trees that are endemic to temperate climates of eastern China and Taiwan, where it has long been cultivated for timber and fuel in forest and agroforestry plantings (Zhu et al. 1986). Rapid growth, favorable wood properties and silvical characteristics of some species make *Paulownia* desirable for many commercial forest products including timber, pulpwood, biomass and biochemicals (Yadav et al. 2013). *Paulownia* species tolerate a broad range of temperature, moisture and fertility regimes (Zhu et al. 1986). We summarized Zhu et al.s' (1986) reported tolerances of three commonly cultivated species of *Paulownia* to environmental stressors in Table 1. Much is known about the cultivation of *Paulownia* in its native China (Zhu et al. 1986) and globally (Yadav et al. 2013), particularly in arid environments where native species are less productive (Sun and Dickinson 1997) and on infertile soils of reclaimed mined land (Tang et al. 1980).

Export of high quality, forest-grown logs from natural stands established following severe canopy disturbances in the U.S. (Williams 1993) suggested growing *P. tomentosa* could prove financially profitable. Because *Paulownia* can grow rapidly to commercial size and growth is substantially enhanced by management activities such as coppicing and fertilization (Beckjord and McIntosh 1983), irrigation (Beckjord 1991), agrocropping (Puxeddu et al. 2012), and pruning (Wu et al. 2014), its cultivation is

Table 1 Characteristics of three *Paulownia* species investigated at Bent Creek Experimental Forest in relation to their relative tolerance of common environmental stressors (Zhu et al. 1986)

Environmental stressor	Relative tolerance		
	P. elongata	*P. fortunei*	*P. tomentosa*
Low light intensity	NA	Moderate	NA
Low temperature	Moderate	Low	High
High temperature	Moderate	Moderate	Moderate
Low atmospheric humidity	Low	NA	Low
High velocity winds	Low	Low	Low
Drought	Moderate	Low	Moderate
Wet soils	Low	Moderate	Low
Flooding	Low	Low	Low
High-clay soils	Low	Moderate	Moderate
Low soil pH (< 5)	Low	Moderate	Low
High soil pH (> 8)	Moderate	Low	Moderate
Low soil fertility	Moderate	Moderate	Moderate

NA: Information not available from Zhu et al. (1986)

particularly well suited for short-rotation silviculture (less than 20 years) by small landowners willing to invest in cultural treatments (Kays et al. 1998; Johnson et al. 2003, Clatterbuck and Hodges 2004).

Early North American research focused on the effects of cultural practices and provenance on *P. tomentosa* growth and yield (Tang et al. 1980; Beckjord and McIntosh 1983; Hardie et al. 1989). Similar tests of other *Paulownia* species followed (Dong and van Buijtenen 1994; Mueller et al. 2001). In the Virginia Piedmont, Mitchem et al. (2002) reported 7-year growth of *P. tomentosa* and *P. elongata* in response to irrigation. Bergmann (2003) evaluated three species of *Paulownia* to age 5 in the Piedmont of North Carolina. These early American studies suggested substantial variability in survivorship, DBH, height and volume by species, good growth response to coppicing, fertilization and irrigation and considerable potential for biomass production. For example, in a Chinese seed source trial, Dong and van Buijtenen (1994) found that *P. elongata* was larger in diameter breast height (DBH) and height compared to *P. tomentosa* after 6 years of growth in east Texas. Early survivorship research results varied widely by species and regeneration type. In east Texas, Dong and van Buijtenen (1994) reported 60% survival of *P. fortunei* after 6 years, but only 20% for *P. tomentosa*. Mitchem et al. (2002) reported survival of approximately 50% for *P. tomentosa* 4 years after coppicing on upland and bottomland sites in central Virginia. At study sites in central North Carolina, Bergmann (2003) found 5-year survival greater than 70% for *P. elongata* and *P. fortunei* regenerated by cloning; however survival of seed-origin regeneration was lower.

Paulownia research has been conducted across a wide variety of ecosystems worldwide. For example, in Turkey, Ayan et al. (2006) compared species physical properties after 1 year of growth and Garcia-Morote et al. (2014) estimated biomass production of individual tree boles after two growing seasons in Spain. Zhu et al. (1986) reported species attained volume comparison trials of *Paulownia* in China. In two studies of stem volume production by four species each, Zhu found *P. elongata* followed by *P. tomentosa* was largest at five years and in another study reported largest production by *P. elongata* followed by *P. catalpifolia*. In one of the few studies of attained volume in unmanaged conditions, Zhu reported 30% greater volume yields of *P. fortunei* compared to *P. elongata* grown in China.

Information is available for managed stand responses to cultural treatments such as weeding, fertilization and irrigation (Beckjord and McIntosh 1983; Donald 1990; Mitchem et al. 2002). Notable exceptions to research of stands managed with cultural treatments are a few mined site reclamation studies where planted Paulownia were left as-is (Jiang et al. 2012; Turner et al. 1988). And past investigations have been short-term in length (less than 8 years from planting). Lacking is information on long term changes in *Paulownia* survivorship, bole diameter, height and attained volume in unmanaged stands undergoing self-thinning, such as those established for non-coppice biomass production or stands established on restoration sites. This information is required by managers as a benchmark to evaluate economic returns from cultural treatments. To our knowledge these attributes have not been reported for unmanaged *Paulownia* stands greater than 7 years of age. Yadav et al. (2013) suggests that studies are needed on productivity of *Paulownia* stands across a range of soils and climates. Tree and stand dynamics information is not available for this genus in the cool, humid environment of the southern Appalachian Mountains. Most U.S.-based silvicultural research has focused on one species, *P. tomentosa* (Snow 2015). Because *Paulownia* species differ in habitat requirements and growth characteristics, managers seek information on which species to plant in relation to varied sites and potential products (e.g. biomass, pulp, timber, fodder).

The primary purpose of our study was to enhance land manager knowledge of growing varied *Paulownia* species by investigating the attained diameter, height and volume of unmanaged *Paulownia* plantings through mid-rotation in the humid-temperate climate of the southern Appalachian Mountains. This study site's tree survivorship at 9 years after planting was previously reported (McNab et al. 2018) and was not a research objective of this current investigation. However, reviewers of an early manuscript draft suggested we should report the likely causes of low (less than 30% after 9 years) survivorship and how our findings compared

with those of others. We agree with these comments and suggest a better understanding of tree survivorship will give readers context for our findings.

We selected for study three globally managed species that have not been evaluated in this region: *P. elongata*, *P. fortunei* and *P. tomentosa*. Our first objective was to review planted tree survivorship through four time periods and suggest likely causes of tree mortality. Our second objective was to characterize species differences in attained DBH, diameter at ground line (DGL) and total height (THT), attributes commonly used by land managers to gauge differences in *Paulownia* tree size by species and time from planting. Our third objective was to develop individual tree stem volume models. Our fourth objective was to characterize stand-level tree density and volume yield differences of the three species. The scope of our study was limited to a single site and did not include cultural treatments, such as coppicing, fertilization, irrigation, weed control or stem pruning, which are typically part of intensive management regimes.

Materials and methods

Our study was established in the Bent Creek Experimental Forest (35.5°N, 82.6°W), an administrative unit of the Pisgah National Forest, which is located in the southern Appalachian Mountains physiographic province of western North Carolina (Fig. 1). This area has a humid continental climate with annual average temperature of 12.8 °C and a seasonal range of 2.3 °C in January to 22.5 °C in July. Annual precipitation averages 121.4 cm and is evenly distributed among the seasons, although occasional brief periods of soil moisture deficits may occur during late summer. The frost-free growing season extends from late April to middle October and averages 157 (SD 14) days.
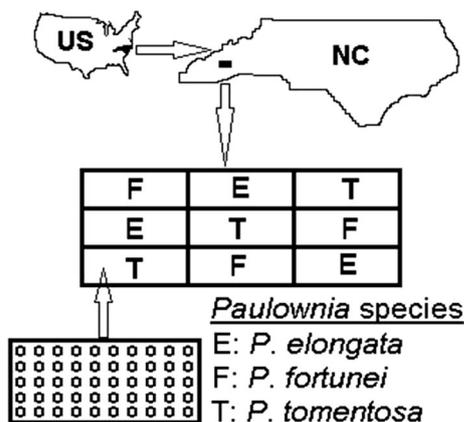

Fig. 1 Vicinity map and experimental design schematic displaying the randomized complete block design; 50 *Paulownia* seedlings were planted in a 5×10 matrix within each of 9, 0.036 ha plots. Bent Creek Experimental Forest, North Carolina, USA

Dominant vegetation consists of a tall (> 30 m) upper canopy of intolerant deciduous hardwoods, (primarily *Quercus* spp. and *Carya* spp.) and a mid-canopy of shade-tolerant tree species, including *Acer rubrum*, *Oxydendrum arboreum* and *Nyssa sylvatica*. Natural disturbances occur from occasional ice storms and downbursts from thunderstorms; wildfire is rare in this humid environment. The 0.32 ha study area was a low elevation (670 m), southwest-facing lower slope that had been cleared of natural vegetation for disposal of sediments removed from a nearby lake. The sediments form a uniform layer of soil material, which is described in greater detail elsewhere (McNab et al. 2018), approximately 60 cm thick with a slope gradient of about 15%. The soil material is classified as a moderate loam that had been derived from weathering of metaigneous gneiss and schist bedrock formations.

Study site weather over the 9-year response period is summarized here because *Paulownia* species have historically exhibited highly varied survivorship and growth responses to temperature and precipitation regimes (Zhu et al. 1986). Winter temperature is a particularly important factor associated with survivorship because cold tolerance varies among species (Table 1). Temperature and precipitation were recorded daily approximately 3 km east of the study site at a similar elevation. Winter temperatures during the study period averaged 4.1 °C and ranged from 1.9 to 5.4 °C. Minimum winter temperature averaged −11.8 °C and ranged from −9.6 to −16.7 °C. The lowest daily winter temperature of −20.6 °C occurred in February after the first growing season. During the second and following years the minimum daily winter temperature was above −11.7 °C. Spring and summer precipitation averaged 67.7 cm and ranged from 53.6 to 115.3 cm. During the third summer a prolonged drought was characterized by total August precipitation of 0.6 cm, compared to the normal monthly amount of approximately 4 cm. High velocity sustained winds of 27 km h^{-1}, with gusts to 93 km h^{-1}, occurred during early October of the first growing season resulting from passage of a subtropical hurricane.

Our study design was randomized complete block with three blocks and three species (treatments) which yielded nine rectangular (10.67 m × 33.54 m) 0.036 ha plots. Each plot was hand planted with one of three species of one-year-old containerized *Paulownia*: *P. elongata*, *P. fortunei*, or *P. tomentosa* obtained from a private eastern Tennessee nursery, on a spacing of 3.3 m between rows and 2.1 m between seedlings within rows, for a total of 50 per plot which represents a density of 1400 per ha (Fig. 1). A corrugated plastic collar (10.2 cm in diameter × 15.2 cm in tall) was placed around each seedling at planting for water conservation, weed control, protection from rodent girdling, and support of the succulent stem from breakage by strong winds during thunderstorms. Seedlings received no

fertilization, cultivation, or weed control and were not coppiced during the study. Competing vegetation on the site at planting consisted primarily of a sparse cover of native grasses and herbs.

Tree survivorship was measured at 1, 2, 4 and 9 years after planting. The THT of each surviving seedling was measured at 1, 2 and 4 years; heights of approximately 25% of all surviving trees were randomly selected for measurement at age 9 because resources were not available to measure all trees. DBH (1.372 m above ground line, outside bark) and DGL of surviving trees were measured at 4 and 9 years after planting. A surrogate variable for total stem volume outside bark (VOL) was estimated as the sum of two sections: (1) the butt section (BUTT) from ground line to DBH, estimated as a frustum of a paraboloid with volume computed using Smalian's formula and (2) a cone for the top section (TOP) from DBH to the stem tip. We examined the distribution of stem volume at 4 and 9 years by calculating the proportion of the total volume present in the BUTT versus the TOP. Approximately 10 trees were excluded that had top-died and re-sprouted. Each of the nine plots was treated as a small even-aged stand for determination of DBH distribution and estimation of productivity.

Data analysis

Objective 1

We calculated survivorship of each species of *Paulownia* measured at age 1 (planting year in October after cessation of growth), 2, 4 and 9 years after planting.

Objective 2

Species by age differences of attained DBH, DGL and THT were evaluated with analysis of variance (ANOVA—with subsampling). Data were analyzed with repeated measures linear mixed models using SAS PROC MIXED (SAS 2013). Results were summarized with least squares means. We also characterized the relationships of DBH with DGL and natural log (ln) transformed DBH with THT by species and stand age through linear regressions. Because the covariances of BLOCK and BLOCK by attribute (e.g. DGL) random effects were not significant ($p > 0.27$) we ignored blocking effects and analyzed data with ordinary least squares for these regressions.

Objective 3

Because land managers may plant varied *Paulownia* species or hybrids not previously tested we decided to develop combined species tree volume models to enable land managers

to predict volumes regardless of species or provenance. Although this combined-species approach may yield a minor loss of accuracy compared to species-specific models, we suggest land managers will find combined species models easier to use.

We developed three combined-species tree volume equations:

(1) $\text{VOL} = f(\text{DBH}^2)$, a simple equation designed to meet the information needs of most land managers, (2) $\ln(\text{VOL}) = f(\ln(\text{DBH}^2 * \text{THT}))$, parameterized to provide greater model accuracy, and (3) $\ln(\text{VOL}) = f(\ln(\text{DGL}^2 * \text{THT}))$, developed to inform land managers of predicted volumes of small stature *Paulownia* trees using diameter at ground line. Because predicted volume was not related to blocking ($p > 0.3$ for block and species × block when tested with PROC MIXED for all three equations) we ignored blocking effects and parameterized volume models with ordinary least squares using SAS PROC GLM (SAS 2013).

We sought to combine years 4 and 9 data to obtain a greater range of tree sizes for developing volume models. To determine if data could be combined we screened our data for differences in residuals of year 4 only versus pooled years 4 and 9 data. Visual review of graphed data points suggested residuals of the two data sets varied only slightly in absolute value (scale) and we concluded that data could be combined. We therefor pooled the 4 and 9 year data by species and deleted year 4 observations of the same trees. We also summarized the proportions of tree volume found within BUTT versus TOP sections by species for all plots.

Objective 4

Using mean attribute values for the three stands (plots) per species, we calculated stand-level DBH, THT, tree density, basal area and volume using the objective 2 model, $\text{VOL} = f(\text{DBH}^2)$.

Results

Objective 1: Planted tree survivorship

Paulownia elongata exhibited superior survivorship at each of the four time periods, followed by *P. fortunei* and *P. tomentosa* (Fig. 2). Final year 9 survivorship was 34% for *P. elongata*, 28% for *P. fortunei* and 21% for *P. tomentosa*.

Objective 2: Attained DBH, DGL and THT

Attained DBH was strongly related to time from planting, species and the interaction of time with species. DGL and THT were strongly related to time and the interaction of time with species (Table 2). Mean DBH ranged from 5.4 to
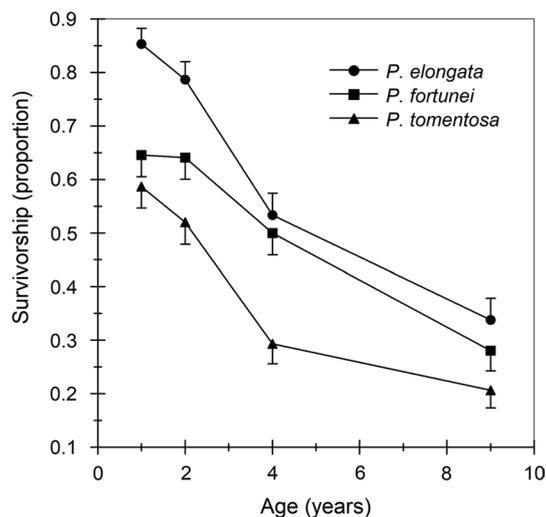
Fig. 2 Survivorship of *P. elongata*, *P. fortunei* and *P. tomentosa* at 1, 2, 4 and 9 years after planting. Standard error bars are one-sided to improve clarity

Table 2 ANOVA fixed effects for attained tree diameter at breast height (DBH in cm), diameter at ground line (DGL in cm) at two times (TIME = 4 and 9 years from establishment) and total height (THT in m) at four times (TIME = 1, 2, 4 and 9 years from establishment) for three species (*P. elongata*, *P. fortunei* and *P. tomentosa*) (SPECIES) of *Paulownia* in Bent Creek Experimental Forest, NC, USA

Variable	Effect	Num DF	Den DF	F Value	Pr > F
DBH[a]	TIME	1	302	397.65	< 0.0001
	SPECIES	2	4	10.69	0.0249
	TIME*SPECIES	2	302	17.04	< 0.0001
DGL	TIME	1	237	231.58	< 0.0001
	SPECIES	2	4	2.74	0.1780
	TIME*SPECIES	2	237	9.57	0.0001
THT[b]	TIME	1	802	1559.14	< 0.0001
	SPECIES	2	4	0.56	0.6090
	TIME*SPECIES	2	802	11.71	< 0.0001

Analyses of variance computed with repeated measures linear mixed models using SAS PROC MIXED (SAS 2013). Time from planting (TIME, in years, expressed as an integer) is a continuous variable

[a] Weighted by 1/standard deviation to reduce heteroscedasticity

[b] Weighted by 1/variance to reduce heteroscedasticity

Random effects block and species by block were not significant ($p > 0.27$ for DBH, THT and DGL analyses)

6.4 cm at age 4 and differed little among the three species (Fig. 3). At age 9, however, DBH was significantly less for *P. fortunei* (11.9 cm) than for either *P. elongata* (15.7 cm) or *P. tomentosa* (17.1). Mean year 4 DGL varied even less than DBH among species, ranging 11.2–11.3 cm. As with DBH, year 9 attained DGL for *P. fortunei* was substantially less than *P. elongata* or *P. tomentosa*. But THT at years 4
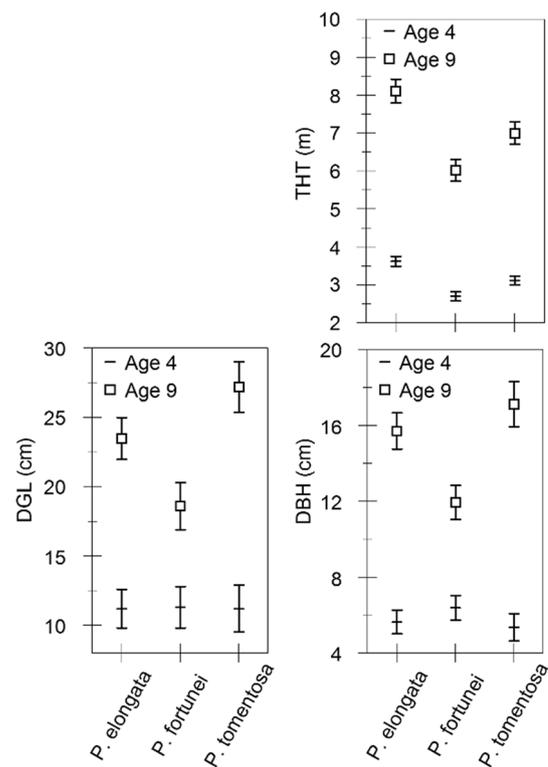

Fig. 3 Least square means and standard errors of diameter breast height (DBH in cm), diameter at ground line (DGL in cm) and total height (THT in m) by stand age and three species of *Paulownia* at the study site in the Bent Creek Experimental Forest, North Carolina, USA

and 9 of *P. elongata* was significantly greater than the other species (Fig. 3). DBH was strongly related to DGL and THT for the 3 species at both 4 and 9 years (Table 3).

Objective 3: Volume

The DBH^2, $\ln(DBH^2*THT)$ and $\ln(DGL^2*THT)$ models explained much of the variation in volume; R^2 was greater than 0.92 with highly significant parameter t values ($p < 0.0001$) for all models (Table 4). Adding height to the DBH^2 volume equation ($\ln(DBH^2*THT)$) increased R^2 only one percent from 0.93 to 0.94 and the root mean square error (RMSE) substantially increased from 0.100 to 0.563 (Table 4). The DBH^2 model exhibited some heteroscedasticity as evidenced by the residual plots in the Fig. 4 inset; heteroscedasticity was less pronounced for the other models. The mean distribution of stem volume at age 4 was approximately 65% in the BUTT and 35% in the TOP and was similar for all species. However, by age 9, except for *P. elongata*, a larger proportion of stem volume was present in the TOP compared to the BUTT (Fig. 5). Because the DBH^2 model will likely be of interest to many land managers we provide here examples of model precision expressed

Table 3 Parameter estimates of linear regression models for the relationship of tree diameter at breast height (DBH in cm) with diameter ground line (DGL in cm) and total height (THT in m) for three species of *Paulownia* at two times from establishment in Bent Creek Experimental Forest, NC, USA

Stand age	Variable	Species	b_0 (SE)	b_1 (SE)	N	F	Pr > F	R^2	SE model
4 years	DGL[a]	*P. elongata*	1.664 (0.491)	1.477 (0.074)	76	401.3	< 0.0001	0.84	2.216
		P. fortunei	1.839 (0.598)	1.434 (0.088)	73	268.5	< 0.0001	0.79	2.223
		P. tomentosa	2.692 (0.626)	1.393 (0.105)	43	175.6	< 0.0001	0.81	1.820
		Combined	1.965 (0.324)	1.441 (0.049)	192	852.9	< 0.0001	0.82	2.133
	THT[b]	*P. elongata*	1.085 (0.213)	2.062 (0.127)	76	263.0	< 0.0001	0.78	0.672
		P. fortunei	−0.084 (0.247)	2.822 (0.140)	73	406.9	< 0.0001	0.85	0.584
		P. tomentosa	1.082 (0.262)	2.081 (0.163)	43	163.5	< 0.0001	0.79	0.580
		Combined	0.751 (0.142)	2.303 (0.084)	192	758.8	< 0.0001	0.80	0.643
9 years	DGL[a]	*P. elongata*	4.490 (1.356)	1.192 (0.074)	47	256.4	< 0.0001	0.845	3.272
		P. fortunei	2.058 (1.463)	1.393 (0.100)	39	195.5	< 0.0001	0.837	5.705
		P. tomentosa	6.460 (1.934)	1.157 (0.107)	31	117.6	< 0.0001	0.795	3.333
		Combined	3.212 (0.890)	1.296 (0.052)	117	625.3	< 0.0001	0.84	4.297
	THT[b]	*P. elongata*	−4.139 (1.808)	5.397 (0.752)	10	51.6	< 0.0001	0.85	1.510
		P. fortunei	4.351 (1.034)	0.368 (0.072)	16	25.8	< 0.0001	0.62	2.735
		P. tomentosa	−7.198 (16.164)	6.565 (5.769)	03	1.3	> 0.05	0.13	0.770
		Combined	0.747 (0.914)	3.730 (0.388)	29	92.5	< 0.0001	0.77	1.868

[a]Model formulation: DGL = $b_0 + b_1$*DBH

[b]Model formulation: THT = $b_0 + b_1$*ln(DBH)

Table 4 Parameter estimates for linear regression models of the relationship of total stem volume (VOL in cubic m) with diameter breast height (DBH in cm), total height (THT in m) and diameter at ground line (DGL in cm) for three species (species data were pooled) of *Paulownia* in Bent Creek Experimental Forest, NC, USA

Model	Intercept (SE)	t	Pr > t	Variable (SE)	t	Pr > t	N	R^2	RMSE
DBH^2[a]	NA	NA	NA	0.0004 (0.000)	58.99	< 0.0001	195	0.93[d]	0.100
Ln (DBH^2*THT)[b]	−8.5006 (0.072)	−118.86	< 0.0001	0.7891 (0.014)	56.39	< 0.0001	195	0.94	0.563
Ln (DGL^2*THT)[c]	−9.8480 (0.044)	−223.02	< 0.0001	0.8590 (0.007)	120.82	< 0.0001	195	0.99	0.389

[a]Model formulation: VOL = b_1*(DBH^2)

[b]Model formulation: Ln (VOL) = $b_0 + b_1$*ln (DBH^2*THT)

[c]Model formulation: Ln (VOL) = $b_0 + b_1$*ln (DGL^2*THT)

[d]R^2 = 1 − (uncorrected error SS-corrected total SS); R^2 adjusted to account for no intercept

Regressions computed with SAS PROC GLM (SAS 2013) as ordinary least squares

as example DBH volume ± the half width of the confidence intervals. For the overall mean DBH of 7.68 cm the volume regression confidence interval (CI) was the predicted volume of 0.02413 ± 0.0008 m³. For a small (e.g. 2.00 cm DBH) tree it was 0.0017 ± 0.0001 m³ and for a large tree (e.g. 17.00 cm DBH) it was 0.1204 ± 0.0040 m³. The overall model regression half width CI was 3.34%.

Objective 4: Stand-level attributes

The total inventory of all trees by DBH class at age 4 revealed similar stand densities for *P. elongata* and *P. fortunei*; *P. tomentosa* density was approximately 40% less than the other two species (Table 5). At age 9, density had decreased for all species, particularly for *P. fortunei* and *P. tomentosa*. Calculation of stand volumes using the DBH^2 models indicated *P. fortunei* was most productive (13.188 m³ ha⁻¹) at age 4 followed by *P. elongata* (13.026 m³ ha⁻¹) (Table 6). Five years later, at age 9, however, stand volume productivity was greatest for *P. elongata* (61.650 m³ ha⁻¹) and least for *P. fortunei* (32.565 m³ ha⁻¹). Stand-level volumes resulted from the interaction of survivorship with individual tree volume; stands with substantially fewer trees also yielded less stand-level volume even when individual trees had larger DBHs. We suggest the stand-level volumes reported in this
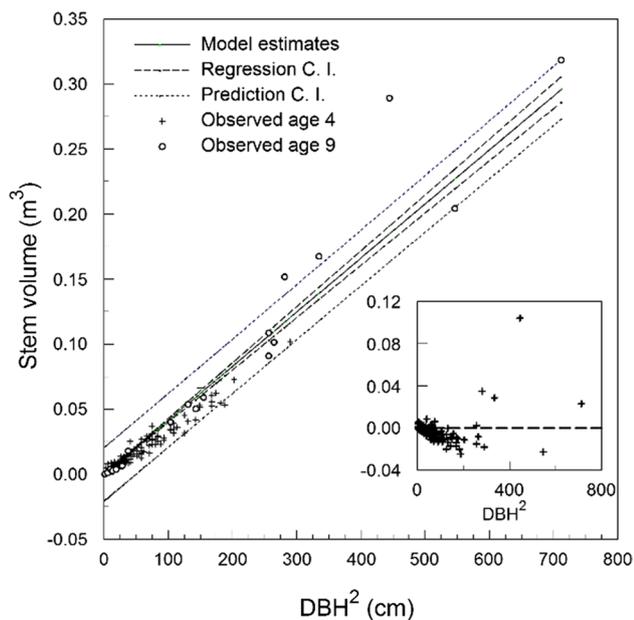
Fig. 4 Combined three species (*P. elongata*, *P. fortunei*, *P. tomentosa*), volume $= DBH^2$ model fitted with ordinary least squares with regression (95% confidence bands) and prediction (95% prediction bands) confidence intervals. The inset shows model residuals versus DBH^2
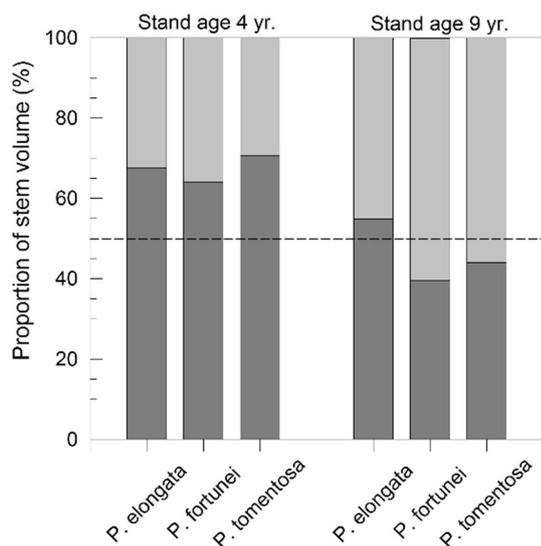

Fig. 5 Proportion of mean total stem volume (m^3) present in the butt (lower, dark section of each bar) and top (upper, light section) for three species of *Paulownia* trees after 4 and 9 years after establishment in the Bent Creek Experimental Forest, North Carolina, USA. The butt section extends from ground line to breast height (1.372 m); the top section extends from breast height to the stem tip

manuscript are a practical metric for managers: overall yield is influenced by both stand-level survivorship and individual tree volume.

Table 5 Mean tree density (SE) by diameter breast height (DBH) class for three species of *Paulownia* at 4 and 9 years after establishment in three unmanaged stands in Bent Creek Experimental Forest, North Carolina, USA

Species	DBH class (cm)	Tree density (ind. ha^{-1})[a]	
		Age 4 years	Age 9 years
P. elongata	0–4.9	381.7 (24.6)	18.6 (18.6)
	5.0–9.9	232.8 (24.6)	37.2 (9.3)
	10.0–14.9	83.8 (42.7)	111.7 (32.2)
	15.0–19.9	9.3 (9.3)	111.7 (58.1)
	20.0–24.9	0.0	121.1 (56.6)
	25.0–29.9	0.0	46.6 (33.6)
	30.0–34.9	0.0	0.0
	Total	707.6 (49.2)	446.9 (100.7)
P. fortunei	0–4.9	251.4 (83.8)	139.7 (64.5)
	5.0–9.9	325.9 (153.3)	55.9 (16.1)
	10.0–14.9	102.4 (65.2)	37.2 (18.6)
	15.0–19.9	0.0	55.9 (27.9)
	20.0–24.9	0.0	37.2 (9.3)
	25.0–29.9	0.0	18.6 (9.3)
	30.0–34.9	0.0	18.6 (18.6)
	Total	679.7 (130.4)	363.1 (100.7)
P. tomentosa	0–4.9	214.2 (134.3)	9.3 (9.3)
	5.0–9.9	158.3 (24.6)	27.9 (16.1)
	10.0–14.9	37.2 (18.6)	37.3 (24.6)
	15.0–19.9	0.0	130.4 (9.3)
	20.0–24.9	0.0	74.5 (24.6)
	25.0–29.9	0.0	18.6 (9.3)
	30.0–34.9	0.0	0.0
	Total	409.7 (144.6)	298.0 (76.2)

[a]Each stand of one species consisted of three 0.036 ha plots. Initial planting density was 1400 ind. ha^{-1}

Discussion

Our 9-year investigation sought to meet land manager information needs of unmanaged *P. elongata*, *P. fortunei* and *P. tomentosa* tree and stand attributes in the western North Carolina Mountains. Based on our research findings, land managers may experience low *Paulownia* survivorship in southeastern U.S. mountain sites. In agreement with the low survival in our study (27.3% for all species at year 9), Johnson et al. (2003) in the Piedmont of Virginia, reported mean *P. tomentosa* survival rates of 11% and 27% after 7 years in control and site prepared areas, respectively. Our study's planted tree survivorship was at the low end of the range of previously reported findings.

Our study's low tree survival was likely related to several unusual weather events during the early years of the study; survivorship dropped precipitously between years 2 and 4 (Fig. 2). Specifically during the third and fourth years of growth summer precipitation was approximately half of

Table 6 Range of diameter ground line (DGL), diameter breast height (DBH), total stem height (THT), mean observed stand density (SE), basal area and predicted stem volume of three *Paulownia* species in three unmanaged stands for each species by time from establishment in Bent Creek Experimental Forest, NC, USA[a]

Stand age	Species	DGL (cm)	DBH (cm)	THT (m)	Density (ind. ha^{-1})	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})[b]
4 years	*P. elongata*	2.5–29.9	1.5–17.0	1.8–7.6	707.6 (49.2)	2.461 (0.772)	13.026 (4.084)
	P. fortunei	2.5–20.6	1.8–13.7	1.7–8.8	679.7 (130.4)	2.492 (0.680)	13.188 (3.599)
	P. tomentosa	2.5–20.8	1.0–11.2	1.5–7.0	409.7 (144.6)	1.121 (0.254)	5.935 (1.344)
9 years	*P. elongata*	5.8–39.9	3.0–28.7	2.1–14.0	446.9 (100.7)	11.649 (4.148)	61.650 (21.955)
	P. fortunei	1.3–45.7	1.0–34.0	2.0–14.5	363.1 (100.7)	6.153 (2.094)	32.565 (11.080)
	P. tomentosa	3.6–38.6	2.5–28.7	10.4–12.0[c]	298.0 (76.2)	7.696 (1.553)	40.729 (8.219)

[a]Each stand consisted of three 0.036 ha plots that were established with 1-year old seedlings planted at spacing of 2.13 m × 3.35 m, or a density of 1400 ind. ha^{-1}

[b]Stem volume calculated using the model formulation: VOL = b_1 (DBH^2) in Table 4

[c]Entire range of tree heights not sampled

normal. During the winter following the first growing season, temperature at our study site reached approximately −20 °C which is below the minimum for the natural range of *P. elongata* and *P. fortunei*, and is near the minimum for the range of *P. tomentosa* (Zhu et al. 1986). The one year old seedlings were further stressed by an early spring freeze occurring in March when temperature dropped to −14 °C. Below freezing temperatures also occurred in April during each year of the study and field crews observed frost damage on several occasions. Dong and van Buijtenen (1994) found that survival of one seed source of *P. tomentosa* in China was particularly sensitive to spring frost damage. Mitchem et al. (2002) reported annual frost damage to *P. tomentosa* at a bottomland study site in the Virginia Piedmont. In early October of the first summer our planting site experienced strong winds from a subtropical hurricane. Although each seedling in our study was partially supported by a 10 cm tall corrugated plastic collar to discourage rodent damage, some were severely buffeted by wind that likely weakened or damaged stems and root systems. Bergmann (2003) reported lower survival of 5-year old *Paulownia* seedlings compared to clones that had been affected by hurricane winds. In summary, we suggest a 2 year drought, recurring spring frosts and a high-velocity wind event likely contributed to our plantation's poor survivorship.

This study's overall low tree survivorship and variation among species could be related to soil properties. Soils at our study site were recently dredged lake sediments from the Late Proterozoic Ashe Metamorphic Suite consisting of mica schist, metasiltstone and metagraywacke (Royall 2003). The sediments are acidic (pH 4.27), low in organic matter (0.005%) and high in total N (369 ppm) (McNab et al. 2018). Turner et al. (1988) reported reduced germination of *P. tomentosa* seeds and lower survivorship of young seedlings in medium with pH < 4.5, although root-shoot ratios did not differ for acidity ranging from pH 4.5–7.0. Melhuish et al. (1990), however, found no difference in survivorship or growth of *P. tomentosa* seedlings between pH ranges of 4.0–6.0. Studies have shown that although *P. tomentosa* and *P. fortunei* grow well on acidic mine tailings, biomass production is improved with amendments that raise soil pH (Tang et al. 1980; Madejon et al. 2014, 2016). The high N content of soil in our study area could have offset the effects of low pH on top growth as suggested by Melhuish et al. (1990). Quality of our soil as a medium for tree growth could not be evaluated because results have not been reported for similar sediments in this region. However, results from an unpublished study of height growth by a native, mesophytic species sensitive to low soil pH showed no difference in site index for trees growing in the lake sediments compared to adjacent undisturbed soil. Survivorship may be related to whether or not seedlings were coppiced. Dong and van Buijtenen (1994) reported high mortality of non-coppiced *P. tomentosa* through age 4 and suggested that coppicing would probably have increased survivorship. Beckjord and McIntosh (1983) recommended spring coppicing of *P. tomentosa* after the first growing season to improve survivorship and stem form.

Our results showed minor differences in mean DBH, DGL and THT among three species of *Paulownia* in unmanaged stands at age 4. By age 9, however, significant differences had developed, particularly for *P. fortunei*, which was smaller in mean DBH, DGL and THT than either *P. elongata* or *P. tomentosa*. Our year 4 results agree with those of Ayan et al. (2006) who studied response to irrigation of three *Paulownia* species in Turkey and after 3 years reported no differences in DBH or THT among *P. elongata*, *P. fortunei* and *P. tomentosa*. Our results also concurred with Mueller et al. (2001) who found no differences of DGL or THT among 2 year old seedlings of the three species. Contrary to our findings of small differences among species in year 4, Sun and Dickinson (1997) reported better two-year height and diameter of *P. fortunei* compared to *P. tomentosa* in a species screening test in a dry tropical environment of Australia.

Our year 9 results disagreed with those of Dong and van Buijtenen ([1994]) who reported larger DBH and THT of *P. fortunei* than *P. elongata* after six years of growth in eastern Texas. In the Piedmont of North Carolina (USA), Bergmann ([2003]) found inconsistent species results after 5-years, with larger DBH and THT of coppiced *P. fortunei* compared to *P. elongata* at one site, but reversed results of the two species at two other distant sites, suggesting varied site fertility and local climate affected research findings.

We suggest our combined-species DBH^2 volume equation (Table [4]) will satisfy the information needs of most land managers. Our DGL^2*THT equation (Table [4]) offers land managers a means of gauging differences in small tree volumes where DBH may be less than approximately 2.0–3.0 cm but DGL has been measured. Predicted all-species volumes computed with our DBH^2 model were less than those of Zhu et al. ([1986]) for *P. fortunei* where DBH exceeded 15 cm. However, Zhu's predicted *P. elongata* volumes closely aligned with those of our all-species model (Fig. [6]). Differences of our findings versus those of Zhu et al. ([1986]) may be an artifact of our use of a cone to estimate TOP volumes; Zhu et al. employed tree taper equations for their volume calculations. Our all-species DBH^2 model predicted volumes were also less than those estimated by the FIA equation [multiple genera equation adopted by the US Forest Service Forest Inventory and Analysis (FIA) program

(Woodall et al. [2011])] with DBH greater than approximately 17.0 cm (Fig. [6]). And compared to the FIA equation, our predicted volumes increased at a slower rate with increasing DBH (Fig. [6]). We found no reports of *stand-level* volume production for any species of *Paulownia*, which was an objective of our study.

Our study had several limitations. First, tree form in our study could have been affected by low survivorship, which resulted in open stands with reduced natural pruning of lower limbs. Next, we adopted a conic profile as a surrogate measure of stem volume above DBH to the tree tip. However, because information on stem profiles is lacking for *Paulownia*, we believe our conical shape served as a satisfactory compromise for TOP volume computation ranging between the extremes of paraboloid and neiloid. And because our volume equation was developed with measured *Paulownia* tree data we suggest our equations may provide land managers with improved volume estimates compared to those provided by FIA's multiple genera (2011) function. Volume equations developed with taper models (e.g. Kozak et al. [1969]; Westfall and Scott [2010]; Zhu et al. [1986]) which characterize nuanced differences in stem form would likely produce more accurate estimates of tree volume than ours. Wu et al. ([2014]) reported that many factors can affect stem form of *P. fortunei* and applying detailed information on *Paulownia* stem taper can improve volume predictions. Clearly, *Paulownia* taper equations are needed for a wide range of tree sizes to inform land managers of differences in attained volume by species. Another limitation was the small size of our study plots, which was restricted by the area of lake sediments forming the planting site. Finally, our study was conducted on alluvial soil sediments removed from a nearby lake which differed in structure and fertility from soils on operational planting sites. Future studies are needed to investigate performance of *Paulownia* on undisturbed soils. However, Zhu et al. ([1986]) reported that soil fertility affects productivity within species, but not among species.
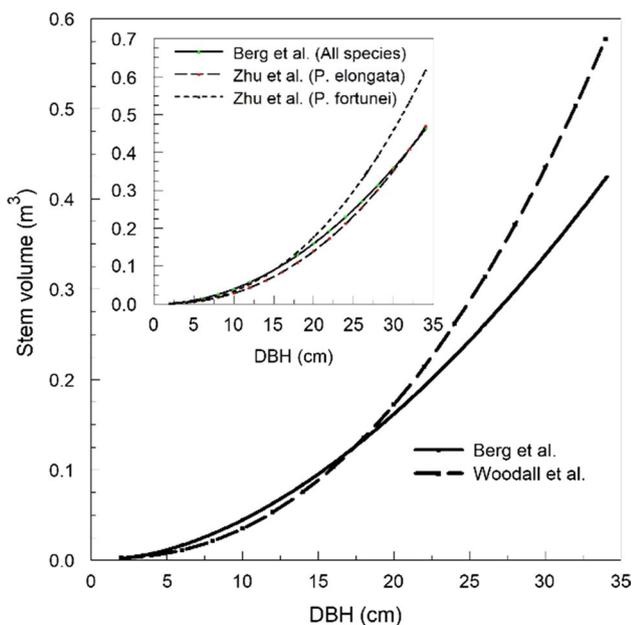

Fig. 6 Predicted stem volume as a function of DBH^2*THT for the combined species *P. elongata*, *P. fortunei* and *P. tomentosa* for this study in comparison with a DBH^2*THT model for multiple genera (applications include *Paulownia*) presented by Woodall et al. ([2011]). The inset shows predicted stem volumes as a function of DBH^2 from this study in comparison with predictions for *P. elongata* and *P. fortunei* presented by Zhu et al. ([1986])

Conclusion

- Survivorship of all species was low (27.3% by year 9); *P. elongata* exhibited the highest survivorship of all 3 species. Low survivorship was likely related to low temperatures, drought and wind damage during the first 3 years of our study.
- The three *Paulownia* species differed little in attained DBH, DGL and THT 4 years after planting. By year 9 *P. fortunei* was substantially smaller in each of these attributes.
- The combined-species volume$=f$(DBH^2) equation provides land managers a tool to predict changes in individual tree volume through mid or end of rotation. Add-

ing total height to this function added little in predictive capability. The volume $= f$ (DGL^2*THT) model offers managers a small diameter (less than 3.0 cm DBH) tree volume estimator.

- The proportion of volume in the butt versus top tree sections declined overall from approximately 65% at age 4–45% at age 9.
- Stand-level attained volume was greatest for *P. elongata* and *P. fortunei* 4 years after planting; by year 9 attained volume of *P. elongata* was 70% greater than the mean of the other two species.
- Our findings generally aligned with those of other southern U.S. *Paulownia* investigators and the Zhu et al. (1986) *P. fortunei* volume equation (Fig. 6). Differences in results may be a function of the small areal size of our research installation and our planting trees in non-native soils. Our volume equations may slightly underestimate tree volumes because we adopted a simple cone to estimate tree form above DBH.

In summary, our study reported estimates of *Paulownia* attributes needed to make long-term land management decisions and can be used to predict yields of unmanaged stands.

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