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Matching site-suitable poplars to rotation length for optimized productivity

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ABSTRACT

Diversity of applications, productivity potential, broad suitability and genetic variations make *Populus* a valuable fast-growing genus. Our goal was to assess if clonal site-suitability varies with rotation-length. We examined survival, growth (height, diameter at breast height) and estimated stem and total-wood (stem and branches) biomass of 89 clones near Fountain, North Carolina (35°42′7.52″ N, 77°34′35.04″ W) in the coastal southeastern USA at four- and eight-year rotations. The unsuitability of some clones was evident at early age while other clones became less suitable with stand age. Specifically, most mortality occurred by year-four, yet 25% clones experienced 17 to 50% mortality at older ages. Clone '379' was the most site-suitable with 100% survival and 141.3 kg total-wood per tree (approximately 47.5 Mg ha^{-1} yr^{-1}). Moreover, several clones with low survival produced high per-hectare biomass. Biomass (stem and total-wood) rankings changed between four- and eight-year rotations with only three top-ten clones in year-four ('379', '402', '449') in the top-ten of year-eight and two top-ten clones in year-eight ('379', '402') also in the top-ten of year-four. Clonal productivity differences increased by 25 to 836% with age. Clones of TD (*Populus trichocarpa* Torr and Gray × *P. deltoids* Barts Ex Marsh) and DD (*P. deltoides* × *P. deltoides*) genotypes were affected by wood infection (*Septoria musiva*) indicating that selection based on disease resistance should be performed at clonal level. Hence, for productivity-focused stands, site-suitable clones should be selected by productivity first, then narrowed by survival and rotation length. Changes in the most 'site-suitable' clones can be expected between longer and shorter rotations.

1. Introduction

Populus spp. and their hybrids are gaining increased attention as a source of wood for producing high-value wood products such as veneer. Recently, Columbia Forest Products Corporation in Boardman, Oregon (USA) launched a successful application of poplars for producing veneer.[1] Poplars are already used both nationally and globally for the production of other wood products including lumber, trim, molding and pulp (Balatinecz et al., 2001; Ares 2002; Fortier et al., 2010 and references therein; Mc Carthy et al., 2018 and references therein; Townsend et al., 2019). In addition, poplars have a great potential for biofuel/bioenergy production, phytoremediation and other ecosystem services (Zalesny et al., 2016). All these prospective poplar applications, along with proven growth potential, make poplars highly valuable short rotation wood crops (SRWCs).

In the southeastern USA, *Populus* species have shown superior early growth and survival compared to native hardwoods (Shifflett et al., 2014; Ghezehei et al., 2019b). Previous studies in the region have mainly focused on examining the productivity potential of poplars as a source of bioenergy feedstock and for land remediation purposes as grown in less utilized and less productive lands (commonly referred to as marginal lands). However, the assessment of poplars for their growth potential to produce logs for high-value wood products or their combined potential to produce feedstocks for high-value wood products (e.g. veneer) and bioenergy in the southeastern USA is lacking. Poplar wood is suitable for biofuel and pulp production (has a high cellulose content) and has good processing quality (cutting, bonding, and finishing) for veneer and is suitable for pulping using various methods (Balatinecz et al., 2001). Previous studies have demonstrated differences in survival, growth and productivity among *Populus* clones and genomic groups under various growing conditions internationally (Lo and Abrahamson, 1996; Pliura et al., 2007; Zalesny et al., 2009, 2019;

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[1] https://www.columbiaforestproducts.com/2013/06/20/columbiaforestproductsboardman/

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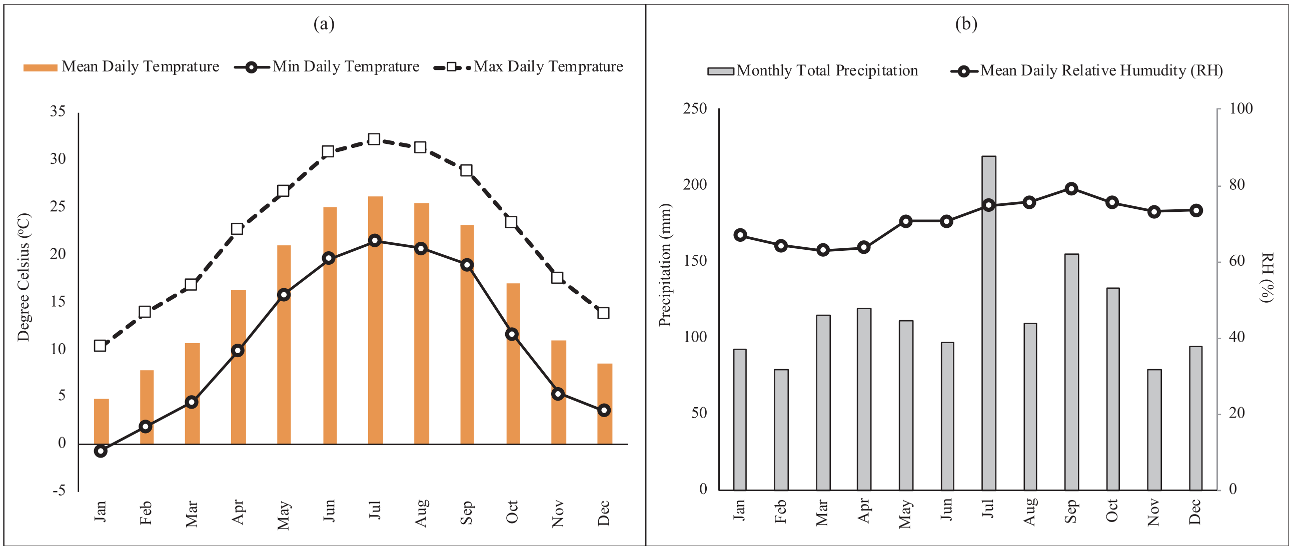

Fig. 1. Four-year averages of (a) daily mean, maximum and minimum air temperatures (degree Celsius), and (b) mean daily relative humidity (%) and total monthly precipitation (mm) based on measurements at the Upper Coastal Plain Research Station (Latitude: 35° 53′ 34.62″ N; longitude: 77° 40′ 47.86″ W).

Table 1
Genomic groups and the general area of origin of the *Populus* clones used for studying genotype effects on survival, tree health and productivity of poplars using an experimental stand located in the Coastal Plain of North Carolina.

Genomic group	Clone	Origin
P. trichocarpa × *P. deltoides* (TD)	185, 187, 188, 229	First-generation/Open-pollinated selection
P. deltoides × *P. deltoides* (DD)	174, 176, 369, 370, 406, 407, 408, 409, 410, 411, 412, 413, 414, 418, 419, 420, 422, 423, 426, 427, 428, 429, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 461, 462	from natural stands, USA
	371, 372, 373, 376, 377, 379, 380, 381, 405	Mississippi
	212, 223, 382, 384, 385, 451	Stoneville, Mississippi
	455, 457, 458	Texas
	447, 448, 449	Texas Forest Service, Texas
	400, 402	Unknown

Fortier et al., 2010; Guo and Zhang 2010; Headlee et al., 2013; Kaczmarek et al., 2013; Nielsen et al., 2014; Pliura et al., 2014; Verlinden et al., 2015; Ghezehei et al., 2016; Ghezehei et al., 2019b). Nevertheless, no single species or genotype can produce optimal gains over a wide-range of climatic and soil conditions of the southeastern USA.

An important consideration when matching poplar clones to environments is the identification of any potential changes in the adaptability of clones to sites with stand age. Such changes would be significant since the rotation length of poplar stands can vary depending on the requirement of particular wood product targeted (Fortier et al., 2010). Depending on the productivity of sites, the production of smaller-diameter feedstock for bioenergy may generally require a rotation of around five years, a ten-year rotation may be required when pulp production is targeted and up to 20 to 30 years may be required to produce poplar stems required for high-value forest products (Stanturf et al., 2001; Fortier et al., 2010). The question of whether poplar clones preferable for shorter rotations (e.g. bioenergy) would be different from those clones that would be suitable for longer-term applications (like pulp or veneer production) is an important consideration when planning poplar plantations at a particular site or region. Kaczmarek et al. (2013) studied 31 commercially-available and irrigated poplar clones in South Carolina USA to the age of ten years, and emphasized the importance of an extensive selection of poplar clones in the search for highly site-suitable varieties in order to maximize productivity of poplars. The study of genetic selection to boost the effectiveness of *Populus* plantations in the southeast USA could be expanded by including clones that are yet to be commercialized. SRWC productivity can be increased by irrigation, yet, with the addition of high costs of installing and maintaining irrigation systems to the already-high costs of establishing and managing SRWCs (Lazarus et al., 2015; Ghezehei et al., 2019a), the feasibility of such plantations under the current demand, markets and feedstock prices for small-diameter biomass could be less appealing. Hence, an extensive study of clonal performances and site-suitability of non-irrigated poplar stands is a worthwhile investigation.

The objective of this study was to conduct an extensive clonal and genomic assessment of survival, susceptibility to wood diseases, growth (height and stem diameter) and productivity (green stem and total-wood biomass) of non-irrigated poplars at early, (one year) mid-rotation (four years) and mature (eight years) ages (as SRWCs) to investigate whether clonal recommendations of poplars for shorter-term and longer-term stand applications would be the same.

2. Materials and metods

2.1. Study site

The study site was located near the town of Fountain (Pitt County) in the Coastal Plain of North Carolina (Latitude: 35°42′7.52″ N, Longitude: 77°34′ 35.04″ W) at an elevation of 24 to 100 m above sea level. Mean total annual precipitation ranges from 965 to 1397 mm (1251 mm to 1715 mm over last five years). The average annual air temperature ranges from 15 to 21 °C; mean daily temperature ranges from −3.8 to 32.8 °C over the last five years. On average, growing season (i.e., number of frost-free days) ranges from 210 to 265 days. Fig. 1 shows five-year averages of daily average, maximum and

Table 2
Survival of the 66 poplar clones located at the study farm in the southeastern Coastal Plain (near Fountain, North Carolina, U.S.A) at the ages of 1 year, 4 years and 8 years (Tree Spacing: 1.23 m × 3.05 m).

Clone	Survival (%)			Affected (#, %)		Clone	Survival (%)			Affected (#, %)	
	1 yr.	4 yrs.	8 yrs.	Infected	Scarred		1 yr.	4 yrs.	8 yrs.	Infected	Scarred
371	100	100	100			**439**	100	83	67		
379	100	100	100			**457**	100	67	67	1 (25)	
381	100	100	100			**462**	83	67	67		
382	100	100	100			**188**	100	67	50		
434	100	100	100			**229**	67	50	50	1 (25)	
435	100	100	100			**402**	83	50	50		
444	100	100	100			**412**	100	83	50		
372	100	100	100		1 (17)	**414**	83	50	50	1 (33)	
407	100	100	100			**423**	67	50	50		1 (33)
420	100	100	100	1 (17)	1 (17	**451**	83	50	50		
435	100	100	100			**212**	67	50	50		
373	100	100	83			**223**	67	50	50		
405	100	100	83			**385**	100	50	50		
432	83	83	83	1 (20)		**418**	100	50	50		
370	100	83	83		1 (20)	**431**	83	50	50		
384	100	83	83	1 (20)	1 (20	**433**	100	50	50		
436	100	83	83			**437**	83	50	50		
438	83	83	83			**440**	100	50	50		
441	83	83	83			**458**	67	50	50		
442	83	83	83			**376**	100	50	33		
447	100	83	83			**369**	100	33	33		
461	100	83	83			**185**	100	83	33	2 (1 0 0)	
413	83	83	83			**377**	100	50	33		
448	100	100	83	1 (20)		**380**	100	33	33		
406	83	83	67			**400**	100	33	33	1 (50)	
419	67	67	67			**409**	33	33	33		
427	100	83	67			**410**	83	33	33		
449	100	67	67			**443**	83	50	33		
176	83	83	67			**187**	83	50	17		1 (1 0 0)
411	100	83	67			**429**	17	17	17		
422	100	83	67			**408**	83	33	17		
426	100	83	67			**174**	83	0	0		
428	100	83	67	1 (25)		**455**	33	0	0		

minimum air temperatures (°C), daily mean relative humidity (%) and total monthly precipitation (mm) based on measurements at the closest weather station of the State Climate Office of North Carolina (located at the Upper Coastal Plain Research Station, latitude: 35° 53′ 34.62″ N; longitude: 77° 40′ 47.856″ W).

The land used for the study had an area of 0.2 ha (0.5 acre) and its slope ranged from flat to 6%. The site had a well-drained Wagram loamy sand (WaB) with a profile deeper than 2 m, and water table was 1.5 to 2 m deep. During the three years preceding the study establishment, the land had been used for growing soybeans, cotton and corn, respectively. To prepare the land, the soil at the site was subsoiled (ripped) to 35 cm depth of in January 2010 and allowed to settle until planting (March 24, 2010). Weed control at establishment included preplanting application of 4.73 L (4.73×10^{-3} m^3) of the post-emergent herbicide Gly-Star® Pro (41% Glyphosate (N-(phosphonomethyl)) glycerine as isopropylamine salt) and the post-planting herbicide applications of 1.89 L (1.89×10^{-3} m^3) of Goal 2XL and 0.089 L (8.87×10^{-5} m^3) of Oust. Weed control during the season included hand-weeding near trees as-needed, spraying herbicide (Gly-Star® Pro) along tree rows using backpacks, between-row broad-spraying of Gly-Star® Pro herbicide and between-row mowing of herbicide-resistant weeds using tractor-towed and walk-behind mowers.

We studied 66 poplar clones planted using a spacing of 1.23 × 3.05 m (2690 trees per hectare). The study clones, their genomic groups, and the general area of their origin are provided in Table 1. Soil water content at planting was moderate. The original experimental design was a randomized block design containing six blocks and one tree of each clone was randomly planted in the subplots. Yet, in a number of cases, some trees representing particular clones in subplots were dead, which made block-related comparisons of growth and productivity ineffective and survival comparisons unrealistic (since values would be either 0 or 100). The study was, therefore, treated as a completely randomized design with replicates (rather than non-replicated randomized block design). The following statistical model was applied:

$$y_{ij} = \mu + \alpha_i + e_{ij}$$

Where: μ is the overall mean of the experiment, α_i denotes the effect of treatments (fixed), which in this study is clones and genomic group and e_{ij} the random error of the experiment.

Two silvicultural practices were carried out during the first-growing season: application of nitrogen fertilizer and basal pruning of multiple stems. Ammonium nitrate (37-0-0) was manually applied along tree rows at the rate of 3.63 t ha^{-1} (a total of 36.4 kg nitrogen) two months after planting, and this was done to ensure that poor site quality would not diminish tree survival, early growth nor root development Trees were pruned on June 17, 2010 to ensure only a single leading stem grew per tree. While this practice may not be very common at commercial plantations, in this study, it enabled the study of productivity with focusing on facilitating quicker size gains of main stems (to target faster growth of the main stem for products that require larger stem diameter).

2.2. Data collection

For this study, it was assumed that after eight to ten years fast growing tree species such as poplars can be considered a mature or even a harvestable plantation (depending on product objective), and that successful SRWCs that could be applied for longer rotations could be identified at this stage. Accordingly, data of survival, tree height and stem diameter at breast height (DBH) were collected one (2010, yr-1), four (2013, yr-4) and eight (2017, yr-8) years after establishment to

Table 3
Tree height and stem diameter at breast height (DBH) averages of the 66 poplar clones located at the study farm in the southeastern Coastal Plain (near Fountain, North Carolina, U.S.A) at the ages of one year, four years and eight years (Tree Spacing: 1.23 m × 3.05 m). Means were separated by age-specific minimum significant differences of height and DBH calculated at $\alpha = 0.05$ ($MSD_{\alpha = 0.05}$).

Clone	Mean height (m)			Mean DBH (cm)		Clone	Mean height (m)			Mean DBH (cm)	
	1 yr.	4 yrs.	8 yrs.	4 yrs.	8 yrs.		1 yr.	4 yrs.	8 yrs.	4 yrs.	8 yrs.
381	2.1 abcd	9.4 abc	9.9 ab	7.3 a	9.7 ab	**437**	2.1 abcd	10.1 abc	12.8 ab	9.2 a	14.6 ab
443	1.9 abcd	9.7 abc	9.9 ab	8.9 a	9.7 ab	**438**	2.2 abcd	11.1 abc	12.8 ab	8.7 a	12.0 ab
440	2.0 abcd	9.5 abc	9.8 ab	6.6 a	8.8 ab	**229**	2.0 abcd	10.5 abc	12.7 ab	9.0 a	13.4 ab
187	2.4 abcd	10.9 abc	9.7 ab	8.1 a	6.9b	**435**	2.6 abc	11.6 abc	12.7 ab	8.3 a	10.0 ab
188	2.6 abc	10.0 abc	9.7 ab	8.1 a	8.4 ab	**441**	2.3 abcd	11.9 ab	12.7 ab	9.2 a	12.3 ab
418	1.8 abcd	8.8 bc	9.5 ab	7.1 a	9.3 ab	**372**	2.5 abc	10.5 abc	12.6 ab	8.2 a	11.1 ab
429	1.7 abcd	8.8 bc	9.5 ab	6.1 a	8.6 ab	**447**	2.4 abc	10.9 abc	12.6 ab	8.8 a	12.0 ab
410	1.5 bcd	8.3c	9.2b	6.7 a	8.3b	**428**	2.3 abcd	11.0 abc	12.5 ab	8.2 a	10.4 ab
379	2.5 abc	11.9 ab	15.2 a	10.6 a	16.3 a	**409**	2.5 abc	9.6 abc	12.3 ab	8.4 a	10.8 ab
445	2.5 abc	12.4 a	14.9 ab	10.8 a	13.9 ab	**223**	2.6 abc	11.4 abc	12.1 ab	8.7 a	10.9 ab
449	2.3 abcd	11.8 ab	14.7 ab	10.4 a	14.5 ab	**423**	2.2 abcd	11.1 abc	12.1 ab	8.9 a	12.6 ab
457	2.4 abc	11.8 abc	14.6 ab	10.3 a	13.6 ab	**419**	2.2 abcd	10.9 abc	11.9 ab	8.5 a	12.2 ab
402	2.5 abc	12.4 a	14.5 ab	10.7 a	16.3 a	**380**	1.6 abcd	9.5 abc	11.8 ab	7.0 a	9.8 ab
462	2.5 abc	12.1 ab	14.4 ab	9.8 a	14.5 ab	**442**	2.5 abc	10.4 abc	11.8 ab	7.6 a	9.7 ab
382	2.7 ab	11.5 abc	14.2 ab	10.0 a	13.6 ab	**431**	2.2 abcd	11.0 abc	11.7 ab	7.6 a	9.6 ab
434	2.8 ab	11.9 ab	14.2 ab	10.1 a	14.0 ab	**432**	2.1 abcd	10.3 abc	11.7 ab	7.3 a	9.9 ab
436	2.7 ab	11.2 abc	14.2 ab	8.7 a	12.4 ab	**422**	2.1 abcd	11.1 abc	11.6 ab	9.1 a	12.6 ab
433	1.9 abcd	11.3 abc	14.0 ab	8.4 a	12.7 ab	**414**	2.1 abcd	11.2 abc	11.5 ab	10.0 a	11.2 ab
212	2.4 abc	12.2 ab	13.7 ab	8.4 a	11.4 ab	**373**	2.8 ab	10.2 abc	11.4 ab	7.8 a	8.8 ab
420	2.5 abc	12.4 a	13.7 ab	9.5 a	11.6 ab	**427**	2.2 abcd	10.5 abc	11.3 ab	6.9 a	9.9 ab
439	2.4 abc	10.9 abc	13.7 ab	8.2 a	11.9 ab	**400**	2.1 abcd	9.9 abc	11.2 ab	6.2 a	10.1 ab
405	2.6 abc	11.7 abc	13.5 ab	9.3 a	12.7 ab	**408**	1.8 abcd	10.3 abc	11.2 ab	8.1 a	10.2 ab
371	2.5 abc	11.4 abc	13.4 ab	10.0 a	14.3 ab	**385**	1.9 abcd	9.8 abc	11.1 ab	7.2 a	9.5 ab
407	2.7 ab	11.6 abc	13.4 ab	9.4 a	12.9 ab	**426**	2.4 abcd	11.7 abc	11.0 ab	7.9 a	10.0 ab
448	2.6 abc	11.7 abc	13.4 ab	10.5 a	13.2 ab	**461**	2.3 abcd	9.8 abc	11.0 ab	6.5 a	9.1 ab
444	2.7 ab	11.1 abc	13.2 ab	9.3 a	12.8 ab	**370**	1.9 abcd	10.5 abc	10.9 ab	7.7 a	10.1 ab
176	2.7 ab	11.4 abc	13.1 ab	9.9 a	11.7 ab	**458**	2.9 a	10.5 abc	10.9 ab	8.7 a	11.2 ab
412	1.9 abcd	11.5 abc	13.1 ab	9.9 a	12.9 ab	**376**	1.7 abcd	11.2 abc	10.8 ab	8.3 a	10.3 ab
377	1.7 abcd	10.7 abc	13.0 ab	9.3 a	13.2 ab	**413**	2.2 abcd	9.7 abc	10.6 ab	7.7 a	10.3 ab
406	2.1 abcd	10.7 abc	13.0 ab	8.8 a	11.4 ab	**185**	2.6 abc	10.8 abc	10.4 ab	10.0 a	11.1 ab
411	1.9 abcd	10.4 abc	13.0 ab	9.5 a	14.4 ab	**451**	2.0 abcd	9.5 abc	10.1 ab	7.4 a	9.6 ab
369	2.2 abcd	10.8 abc	12.9 ab	7.7 a	10.3 ab	**174**	1.3 cd	–	–	–	–
384	2.7 ab	10.4 abc	12.8 ab	8.6 a	11.6 ab	**455**	1.1 d	–	–	–	–
$MSD_{\alpha = 0.05}$	1.32	3.53	6	5.07	8						
CV	21.9	10.5	14.3	18.9	20.3						

Means with the same letter within a column are not significantly different.
$MSD_{\alpha=0.05}$: Minimum significant difference at $\alpha = 0.05$.
CV: Coefficient of variation.

monitor clonal survival, growth, and woody biomass productivity at early, mid-rotation, and mature ages. The early-age was used to examine establishment of the clones and the mid-rotation age was selected to examine the suitability of clones for the production smaller-diameter stems (for bioenergy or even close to pulpwood under highly productive conditions). The mature-age was included to examine clones for larger-diameter production (under the above-mentioned assumption), which could take longer than 10 years but only limited changes in clonal ranks and suitability could be expected. As an additional parameter of assessing site-suitability of study clones, an inventory of tree wood heath was conducted at mature age (nine years of age).

Tree height was used to study growth starting in year one (yr-1) when a great number of trees were shorter than breast-height (1.3 m above ground). Diameter at breast height (DBH) was measured at yr-4 and yr-8 to track growth in a way relatable to tree log production for the purpose of producing particular end-products that are sensitive to stem sizes (requiring minimum sizes). Green stem biomass per tree (kg) was estimated using an equation developed by destructively sampling (carried out in May 2018) 49 trees consisting of seven trees of seven clones ('140', '176', '185', '187', '188', '229' and '356') from a five-year-old research stand located in the Coastal Plain of North Carolina (Williamsdale Research Farm, latitude: 34° 45′ 50.76″; longitude: 78° 5′ 53.88″). Three size-classes (i.e., smallest-, middle-, and biggest-third) were formed per clone (that were planted in groups of 16-trees) based on DBH measurements made at the sampling site at the end of the preceding year (2017). The classes were the smallest-third, the medium-third and the biggest-third. From each clone, trees were randomly selected for sampling to include two from the smallest size-class, three from the medium class and two from the largest class. Prior to the destructive sampling, DBHs of all trees were measured. Fresh stem biomass was determined by weighing main stems of the sampled trees after removing all leaves and branches. Total green wood biomass per tree (kg), which included stem and branches, was estimated using an equation by Ghezehei et al (2019b). That is,

$$\text{Green wood biomass (kg)} = 2656.7 \times \text{DBH}^2 - 0.2923$$

The GSB-versus-DBH allometric equation developed using data obtained by destructive sampling is given in Equation (3). GBS and DBH had a strong and reliable correlation with a high coefficient of determination (R^2 greater than 0.98). Hence, the equation was used to estimate GSB using DBH for the study of clonal and genomic effects on GSB (current study).

$$\text{GreenstemBiomass(GSB)} = 0.1375\text{DBH}^{2.3681} \quad (3)$$

Where: GSB is in kg per tree and DBH is in cm.

2.3. Data analyses

An allometric equation of fresh green stem biomass (GSB) versus DBH was developed using the data obtained by the destructive sampling of the 49 poplar trees, and the validity of the equation was examined using the coefficient of determination (R^2). To examine effects

Table 4
Mean green stem biomass (GSB) per tree of the 66 poplar clones located at the study farm in the southeastern Coastal Plain (near Fountain, North Carolina, U.S.A) at the ages of four and eight years (Tree Spacing: 1.23 m × 3.05 m). Means were separated by age-specific minimum significant differences of GSB calculated at α = 0.05 ($MSD_{\alpha = 0.05}$).

Clone	Mean GSB (kg)		Clone	Mean GSB (kg)	
	4 yrs.	8 yrs.		4 yrs.	8 yrs.
379	37.0 a	100.7 a	**212**	21.5 a	43.5 abc
402	37.6 a	99.2 ab	**372**	21.1 a	43.5 abc
411	31.0 a	80.3 abc	**458**	23.7 a	42.0 abc
437	27.2 a	80.3 abc	**185**	32.9 a	41.0 abc
462	31.3 a	77.4 abc	**223**	24.2 a	40.6 abc
371	32.2 a	76.3 abc	**409**	21.4 a	39.2 abc
449	35.5 a	76.1 abc	**376**	22.6 a	39.1 abc
434	33.4 a	71.4 abc	**413**	18.4 a	36.0 abc
445	39.1 a	70.6 abc	**428**	21.2 a	35.9 abc
382	32.5 a	66.4 abc	**400**	11.5 a	35.7 abc
457	34.4 a	65.9 abc	**370**	19.2 a	34.6 abc
448	38.9 a	65.7 abc	**427**	14.9 a	34.2 abc
229	25.4 a	64.5 abc	**369**	17.4 a	34.1 abc
412	33.1 a	63.4 abc	**435**	21.8 a	33.3 abc
433	22.9 a	61.2 abc	**408**	19.8 a	33.2 abc
377	27.2 a	60.2 abc	**426**	19.1 a	32.9 abc
423	25.9 a	59.8 abc	**381**	16.9 a	32.8 abc
444	28.4 a	59.4 abc	**432**	16.2 a	32.2 abc
407	27.8 a	58.2 abc	**442**	17.8 a	32.0 abc
405	27.6 a	57.2 abc	**380**	14.4 a	30.5 abc
422	25.9 a	56.1 abc	**443**	27.1 a	30.3 abc
419	24.9 a	56.0 abc	**451**	16.6 a	29.8 abc
436	23.7 a	54.4 abc	**431**	17.2 a	29.2 abc
438	26.3 a	53.8 abc	**385**	15.0 a	28.8 abc
441	27.0 a	53.2 abc	**418**	15.1 a	28.5 abc
447	25.4 a	52.2 abc	**461**	11.9 a	26.8 abc
384	24.2 a	51.4 abc	**373**	19.2 a	24.1 bc
439	21.1 a	47.6 abc	**440**	12.4 a	23.6 bc
420	29.8 a	46.8 abc	**410**	13.7 a	23.2c
176	33.0 a	46.1 abc	**429**	10.2 a	22.8c
414	38.5 a	46.0 abc	**188**	20.3 a	22.2c
406	24.8 a	45.2 abc	**187**	20.7 a	13.4c
$MSD_{\alpha = 0.05}$	32.9	75.7			
CV	42.8	45			

Means with the same letter within a column are not significantly different.
$MSD_{\alpha=0.05}$: Minimum significant difference at α = 0.05.
CV: Coefficient of variation.

of clones and genomic groups on height, DBH, and stem and total-woody biomass at various ages (yr-1 for height and yr-4 and yr-8 for all parameters), GLM (generalized linear model, α = 0.05) was applied using Proc GLM of SAS (SAS 9.4). To check the significance of differences in (or to separate) clonal and genomic means of growth and productivity, variable-and age-specific minimum significant differences at α = 0.05 ($MSD_{\alpha = 0.05}$) were used.

3. Results

3.1. Clonal effects

3.1.1. Survival

Only 12 clones maintained 100% survival from yr-1 to yr-8 (Table 2). Of the 18 clones with yr-8 survival of 83%, three had 100% survival on yr-4 (indicating mortality after yr-4), seven clones maintained 83% survival since yr-1, and the remaining clones had 83% survival since yr-4, which implied that the 17% mortality occurred in second or third years of growth. Among clones with yr-8 survival of 50% or lower, four clones had the same survival from yr-1 whereas 73% had the same survival since yr-4. Clones '174' and '455' were dead by yr-4 although the former had high yr-1 survival (83%). Overall, 25% of the clones maintained the same survival from yr-1 to yr-8, 27% of the clones had the same survival in yr-1 and yr-4, and most (75%) clones had the same survival in yr-4 and yr-8.

3.1.2. Susceptibility of wood diseases

Ten (≈ 16%) of the study clones were affected by wood infection caused by *Septoria musiva* (Table 2) although the percentage of affected trees of the clones were different. Wood scars (without active infection) were observed on six (9% of the) clones. Only two clones ('384' and '420') were affected by both wood infected and wood scars.

3.1.3. Growth and wood biomass productivity

The only clonal significant height differences in yr-1 (Table 3) were between clone '458' and the shortest-three clones. By yr-4, the tallest-three clones were significant taller than the shortest-three clones ('418', '429' and '410') despite no significant differences among most clones and clones '429' and '410' in yr-1. Height differences among 97% of the living clones in yr-8 were not significant. Clonal DBH differences in yr-4 were insignificant (Table 3). In yr-8, only two clones ('379' and '402') had significantly greater DBHs than other two clones ('187' and '410'). Clone '373' had low rankings of both height and DBH, and other clones with low DBH rankings were mostly shorter than most clones, although the height differences were not significant.

There were significant differences in GSB at yr-8 but not yr-4 (Table 4). In eight years, clones '379' and '402' produced per-tree GSB that was at least two times the GSB produced by 57% (or 37) of the study clones. Nevertheless, while clone '379' was the best overall performer at the site due to high survival (100%) and greater GSB, the overall productivity of clone '402', is expected to be low due to the poor survival (50% by yr-8). Fifty percent of the clones that survived to yr-8 were intermediate to high GSB producers (58.2 to 73.6 kg per tree) while another five clones had low GSB (50 kg per tree or lower). All clones with poorest survival in yr-8 (17%) also had low GSB productivity (≤33 kg per tree or ≤ 28% of the highest GSB). Similarly, other clones with low survival (33%) were mostly poor GSB producers (< 41 kg per tree or ≤ 35% of the highest GSB) with the exception of clone '377' whose live trees produced yr-8 GSBs of 60 kg per tree (51% of the highest GSB) and 70 kg per tree (60% of the highest GSB), respectively.

Taking into account survival and per-tree GSB, numerous clones achieved mean annual GSB increments of 10 Mg ha^{-1} (80 Mg ha^{-1} in yr-8) or greater (Fig. 2). These clones include all clones with 100% survival, 72% of the clones with 83% survival, and 75% and 41% of the clones with 67% and 50% survival, respectively. Although the greatest GSB (179 to 217 Mg ha^{-1}) was produced by four clones with 100% survival ('382', '434', '371' and '379'), some clones with lower survival produced greater GSB than other clones with higher survival. For example, one clone with 50% survival ('402') produced greater mean GSB (133 to 158 Mg ha^{-1}) than eight clones with 67% survival, seven clones with 83% survival and four clones with 100% survival. Likewise, four clones with 67% survival produced greater mean GSB (137 to 146 Mg ha^{-1}) than eight clones with 83% survival and four clones with 100% survival. Lastly, five clones with 83% survival produced comparable or greater mean GSB (140 to 165 Mg ha^{-1}) versus eight clones with 100% survival.

Clonal differences in green total-wood biomass (GWB) after four years of growth were insignificant (Table 5). In yr-8, clonal per-tree GWB ranged from 15.1 to 141 kg with clone '379'' having the highest per-tree GWB (141.3 kg), which was significantly greater than GWB of clone '187' (the lowest). Similar to the GSB, the overall (per-hectare) GWB productivity of some clones (e.g. '402') would be limited by low survival whereas greater mean GWB (141.3 kg per tree) and high survival of clone '379' is an indication of the suitability of the clone at the site.

A large number of clones produced mean annual GWB increments of 14.3 Mg ha^{-1} (114.3 Mg ha^{-1} in yr-8) or greater (Fig. 3), *including* ten out of the 12 clones with 100% survival, two-third of the clones with 83% survival, 56% of the clones with 67% survival and a third of the clones with 50% survival. The greatest GWB producers were clones with 100% survival. Nevertheless, several cases of comparable clonal

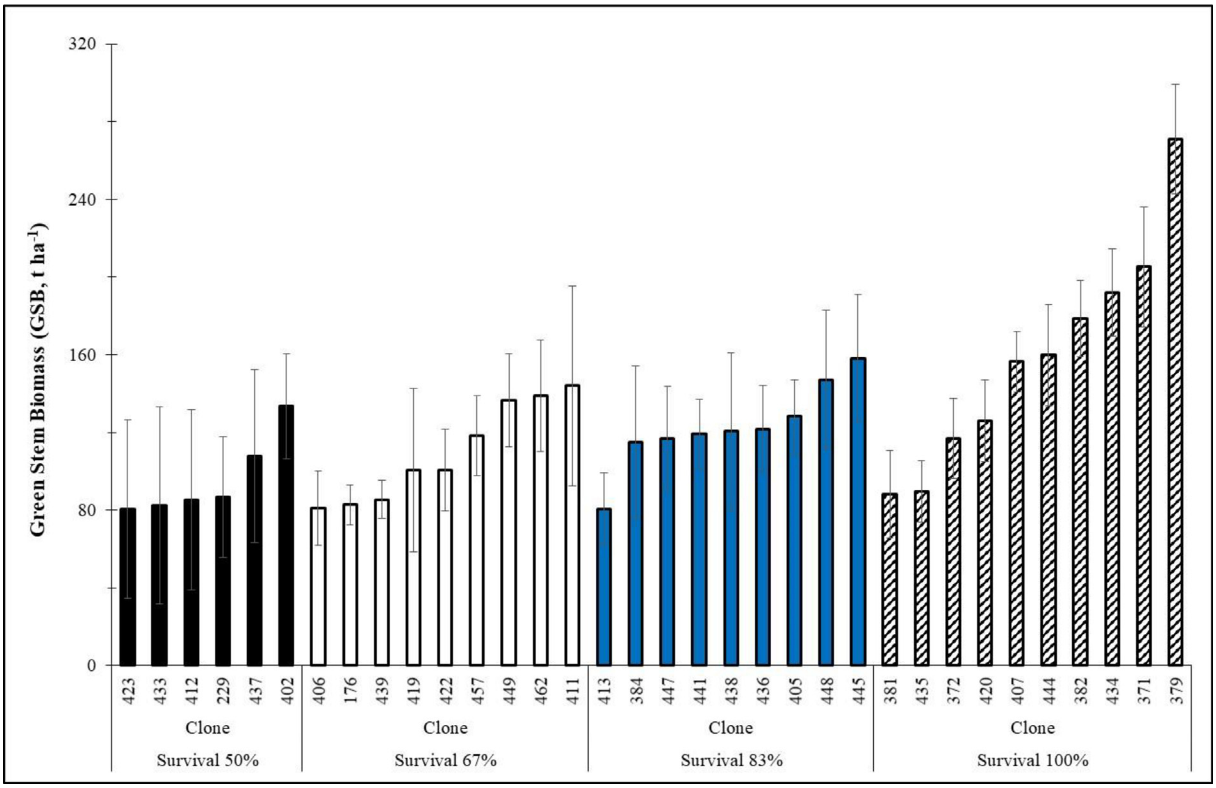

Fig. 2. Poplar clones located in the southeastern Coastal Plain (near Fountain, North Carolina) with mean annual green stem biomass (GSB) increment of 10 Mg ha^{-1} (80 Mg ha^{-1} in eight years) or greater and 50 to 100% survival (error bars stand for ± 1 standard error).

GWB (Mg ha^{-1}) productivities were observed across survival levels. That is, four clones with 50% survival, two clones with 67% survival and two clones with 100% survival had comparable GWBs (111 to 124 Mg ha^{-1}). Twelve clones with survival of 50%, 67%, 83% and 100% had GWBs within 10% of their mean productivity (141 to 170 Mg ha^{-1}), and nine other clones across the four survival levels also had GWBs within the range of 177 to 202 Mg ha^{-1}. Finally, the highest GWB-producing clone with 50% survival and five clones with 83% and 100% survival had close GWB values (215 to 226 Mg ha^{-1}).

3.2. Genomic groups effects

The survival of both genomic groups in yr-1 was high (88%) but DD genotype had 6% and 35% higher survival in yr-4 and yr-8, respectively. Effects of genomic groups on the growth and productivity (wood biomass) of poplars were not significant (Table 6). Nonetheless, after four years, TD clones had a minimal advantage over the DD clones for most of the growth and biomass parameters of growth and biomass (DBH, GSB and GWB). The reverse was true in yr-8 for all growth and biomass parameters. Based on the clones studied, in genotype had no effect in the resistance to *Septoria* wood disease and the wood infection and wood scars affected clones that belong to both TD ('185', '187' and '229') and DD ('372', '420', '432', '370', '384', '428', '457', '400', '414' and '423') genotypes.

4. Discussion

Identifying suitable SRWCs from long-term field studies that assess productivity, survival, and tree health from early to mature ages can help to inform and maximize the efficacy of fast-growing plantations (Lo and Abrahamson, 1996; Ares 2002; Kaczmarek et al., 2013). Our study achieved this by examining the suitability of a wide variety of poplar clones starting from establishment to an age often regarded as mature for most applications of short rotation forestry. Such studies enable the identification of clones with faster early-growth along with those having faster growth rates at later ages, and facilitate recommendations of the most suitable clones based on particular stand objectives, targeted use of the wood from stands and expected stand rotations.

Most clones in this study had the same survival during yr-4 and yr-8, indicating that yr-4 survival was more reliable than yr-1 for predicting survival at mature age. In addition, only 25% of the clones had the same survival in yr-1 and yr-4, which contradicted with the results of Kaczmarek et al. (2013) who indicated minimal clonal differences in survival between years one and three for most of their genotypes. Instead, our results generally agreed with the findings of Ares (2002) where survival after year-three was low. One of the important early indicator of long-term poplar suitability at a site is root development, and year-one survival is indicative of root development (Ares 2002; Kaczmarek et al., 2013). Poplar clonal differences in root establishment and physiology (functional performance) and distribution are expected, and clones selected with high root-adaptability to local soil conditions are preferred (Mc Carthy et al., 2018) and the selection of such clones should be established through long-term and comprehensive root studies (Stuhlinger and Toliver, 2001).

Clonal susceptibility to wood diseases should be a critical consideration when selecting clones for commercial plantations. In our study, three high-productivity ('448', '457' and '229') and two medium-productivity ('384' and '420') clones showed wood infections that renders them unsuitable for large-scale plantations. Due to susceptibility to wood scars, clone '372', which has medium GWB, high survival and high overall productivity (Fig. 3), has low suitability for commercial plantations that are grown for high-quality wood products (e.g. veneer). Leaf rust (by *Melampsora medusae*) affected many clones towards the end of growing seasons, with some noticeable differences in the extent of infection among clones but is of lower concern the above-mentioned wood infections. No pests threats were observed at the study site.

Table 5
Mean green total-wood biomass per tree (GWB) of the 66 poplar clones planted at the study farm in the southeastern Coastal Plain (near Fountain, North Carolina, U.S.A) at four and eight years of age (Tree Spacing: 1.23 m × 3.05 m). Means were separated by age-specific minimum significant differences of GWB calculated at α = 0.05 ($MSD_{\alpha\ =\ 0.05}$).

Clone	Mean GWB (kg)		Clone	Mean GWB (kg)	
	4 yrs.	8 yrs.		4 yrs.	8 yrs.
379	46.7 a	141.3 a	**372**	25.2 a	56.4 abc
402	47.5 a	138.8 ab	**212**	25.5 a	55.7 abc
411	38.8 a	111.3 abc	**458**	28.5 a	53.8 abc
437	33.3 a	110.5 abc	**185**	41.1 a	52.2 abc
462	38.9 a	105.7 abc	**223**	29.4 a	52.0 abc
371	40.1 a	104.4 abc	**376**	27.5 a	50.7 abc
449	44.5 a	103.7 abc	**409**	25.5 a	49.8 abc
434	41.8 a	96.6 abc	**400**	13.0 a	45.6 abc
445	49.6 a	96.0 abc	**413**	21.8 a	45.6 abc
382	40.4 a	89.2 abc	**428**	25.4 a	45.3 abc
448	50.0 a	88.9 abc	**370**	22.9 a	43.8 abc
457	43.1 a	88.4 abc	**427**	17.3 a	43.3 abc
229	30.9 a	86.7 abc	**369**	20.2 a	42.7 abc
412	41.6 a	85.7 abc	**435**	26.2 a	41.9 abc
433	27.8 a	82.6 abc	**381**	19.9 a	41.6 abc
423	31.7 a	80.4 abc	**408**	23.3 a	41.3 abc
377	33.1 a	79.8 abc	**426**	22.5 a	41.2 abc
444	35.0 a	79.3 abc	**432**	18.9 a	40.2 abc
407	34.0 a	77.1 abc	**442**	20.9 a	40.1 abc
405	33.7 a	75.7 abc	**380**	16.4 a	37.6 abc
419	30.7 a	75.0 abc	**443**	33.7 a	37.5 abc
422	31.4 a	74.1 abc	**451**	19.4 a	36.8 abc
436	28.6 a	71.8 abc	**431**	20.0 a	36.0 abc
438	32.7 a	71.8 abc	**385**	17.2 a	35.4 abc
441	33.0 a	69.9 abc	**418**	17.5 a	35.2 abc
447	31.1 a	68.9 abc	**461**	13.4 a	33.0 abc
384	29.6 a	68.6 abc	**373**	22.9 a	29.2 bc
439	25.2 a	61.6 abc	**410**	15.7 a	28.4c
420	37.0 a	61.0 abc	**440**	13.9 a	28.3c
414	50.4 a	60.4 abc	**429**	11.2 a	27.3c
176	41.5 a	59.5 abc	**188**	24.2 a	26.7c
406	30.1 a	58.4 abc	**187**	24.6 a	15.1c
$MSD_{\alpha\ =\ 0.05}$	**44.7**	**109.9**			
CV	**42.9**	**49.5**			

Means with the same letter within a column are not significantly different.
$MSD_{\alpha=0.05}$: Minimum significant difference at α = 0.05.
CV: Coefficient of variation.

The comparison of the results from the current and previous studies conducted in the Coastal Southeastern region of the USA highlights the value of an extensive clonal screening in order to enhance site suitability and efficacy of poplars as SRWCs. For instance, the height and DBH values in this study were mostly greater than poplar heights and DBHs reported in Kaczmarek et al. (2013), with more than 56% of clones in our study showing greater yr-8 heights than their maximum ten-year height of the above study. Likewise, 35 clones in this study had greater yr-8 DBHs than the greatest ten-year clonal DBH in Kaczmarek et al. (2013). In the current study, a baseline mean GSB increment of 10 Mg ha^{-1} yr^{-1} was selected for comparing clonal GSBs. Our goal was to assess the suitability of a large number of clones to the study site by comparing the clones against one another, and the selected baseline value represented 25% of the maximum clonal stem biomass productivity that was possible at the site (117.2 kg tree^{-1} in eight years, which, assuming 100% survival, would be 315 Mg ha^{-1} or ≈ 39.4 Mg ha^{-1} yr^{-1}). The value 14.3 Mg ha^{-1} yr^{-1} used as a GWB reference point was based on Ghezehei et al (2019b) who found that, on average, 69.8% of poplar wood was stem. Our results of lower-survival clones potentially producing greater per-hectare wood biomasses (GSB and GWB) than some higher-survival clones agreed with the study of Ares (2002), who concluded the absence of direct correlation between survival and growth of clones. Some lower-survival clones producing comparable or higher biomass versus higher-survival clones may suggest that in single-clone plantations the former could be preferable since greater resource availability for live trees could increase productivity and alleviate biomass loss due to mortality. Some clones studied here ('419' and '445') that produced greater biomass than higher-survival clones had the same (relatively lower) survival from yr-1 to yr-8 (mature-age). For these clones, although replanting after year one is an option that can be considered to maintain original stocking levels, it may not increase stand productivity of the clones.

Previous studies correlating poplar growth and productivity at early and mature ages led to contradicting outcomes with some positive and negative correlations (Ares 2002 and references therein; Kaczmarek et al., 2013). Ghezehei et al. (2019b) found significant biomass differences among some four-year-old poplar clones in the coastal southeastern USA. In the current study, clonal differences in stem biomass (per tree) were significant during yr-8 but not yr-4, and this could indicate the possibility of differences becoming more significant as trees reach stand maturity. These findings imply that: 1) a greater emphasis on narrowing the selection of suitable clones based on survival, health and productivity may be required for longer rotations than shorter rotations, 2) it is possible to identify different clones as highly suitable for a particular site in shorter and longer rotations, and 3) there is a need to identify clones with faster growth rates at later ages. In the current study, wood biomass differences between the most productive clone (on a per-tree basis) and the other clones were largely greater with age (with 25% to ≈ 900%), which agreed with the results of Kaczmarek et al. (2013), although the increase in biomass gaps with age were greater in the latter (year-three 1400% to year-ten 3200%). Some clones of the same genotype had great biomass differences (in yr-8), which agrees with results from Ghezehei et al. (2019b). In contrast to the findings of several studies (Heilman et al., 1994; Ceulemans and Deraedt, 1999; Benetka et al., 2002; Dillen et al., 2013; Verlinden et al., 2013; Benetka et al., 2014), neither the interspecies (TD) nor the intraspecific (DD) hybrid poplars in the current study had superior wood biomass productivity.

The GDB and GWB (productivity) values reported require careful interpretation. Trial productivities tend to overestimate potential production-scale productivities (Zalesny et al., 2009; Ghezehei et al., 2019b). Another consideration is that, in this study, the placement of clones relative to one another was randomized (as individual trees), and the clonal productivities reported will likely vary from productivities of the same clones when grown as homogeneous stands (Ares 2002). Both the inventoried and biomass-sampling sites of this study were in the Coastal southeastern USA and were only 106 km apart. Nevertheless, the use of an allometric equation derived for a different locality could lead to discrepancies due to differences in site and stand variables (such as, site index, stand age) and clonal differences in biomass allocation (Fortier et al., 2010, 2017; Headlee and Zalesny, 2019). However, it is unlikely that the use of the DBH-GSB allometric correlation in this study led to biases among clones.

In the southeast USA, fertilization of purpose-grown stands to enhance their productivity is not uncommon (Fox et al., 2007; Coyle et al., 2008; Albaugh et al., 2019). In this study, all treatments were fertilized to ensure that poor site quality would not diminish tree survival, early growth nor root development, and this intent was in line with previous observations that showed that fertilizer application during poplar establishment led to increased growth (van den Driessche 1999; Guillemette and DesRochers 2008). Hence, the differences in survival mainly, and height to some extent, in yr-1 of our study were due to clonal effects and not poor soil fertility. Coyle et al. (2016) found that both above-and below-ground biomass of poplar genotypes increased with fertilization, with yearly fertilizations leading to enhanced productivities (versus non-fertilized) in the first four years only. Given the common general-locality of their study and our study (Coastal southeast USA) and baring differences in the specific localities of the studies, annual fertilization in our study would likely lead to greater yr-4 productivity values than reported. Assessing whether productivity enhancements resulting from annual fertilizations in the first four years

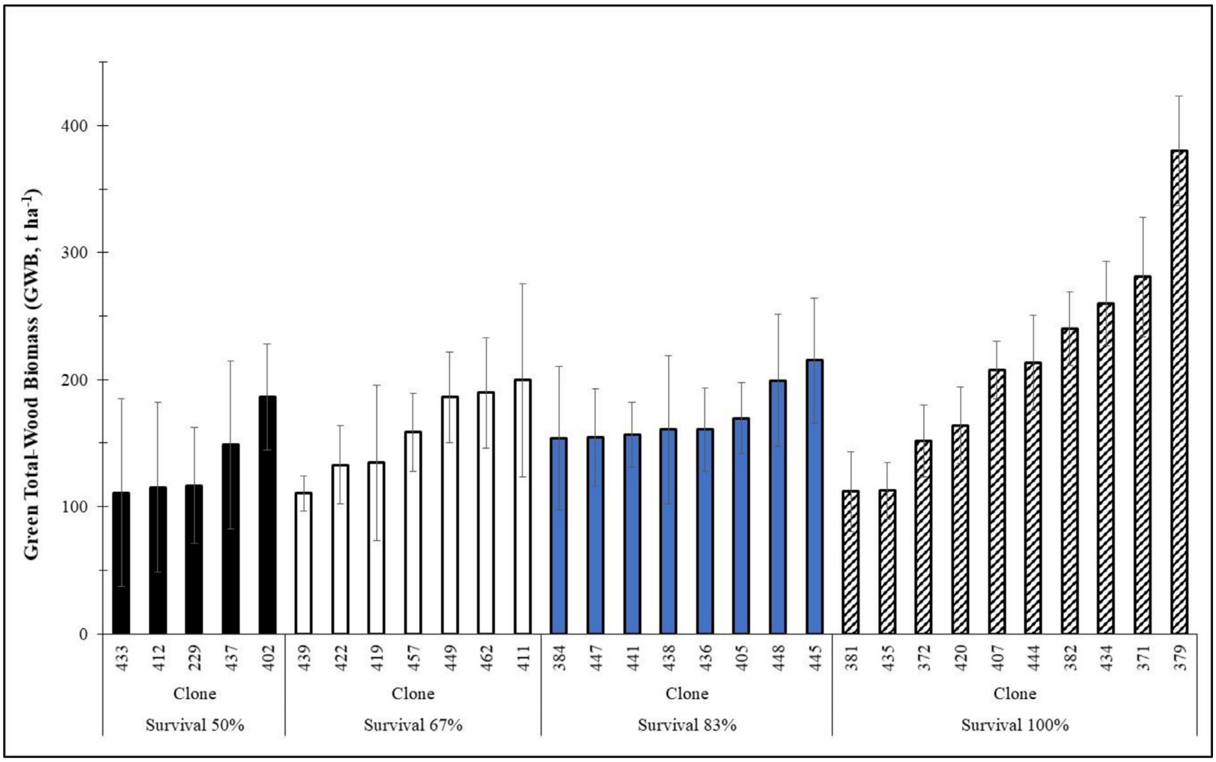

Fig. 3. Poplar clones located in the southeastern Coastal Plain (near Fountain, North Carolina) with mean annual green total-wood biomass (GWB) increment of 14.3 Mg ha^{-1} (114.4 Mg ha^{-1} in eight years) or greater and 50 to 100% survival (error bars stand for ± 1 standard error).

Table 6
Analyses results of the effect of poplar genomic groups (*P. trichocarpra* × *P. deltoids* 'TD' and *P. deltoides* × *P. deltoides* 'DD') on tree height, stem diameter at breast height (DBH), per-tree green stem biomass (GSB), and per tree green total-wood biomass (GWB) at the ages of four and eight years (Location: Coastal Plain, near Fountain, North Carolina, U.S.A). Means were separated by age-specific minimum significant differences calculated at α = 0.05 ($MSD_{\alpha\ =\ 0.05}$).

Parameters		Mean height (m)		Mean DBH (cm)		Mean GSB (kg)		Mean GWB (kg)		Mean survival (%)		
		4 yrs.	8 yrs.	4 yrs.	8 yrs.	4 yrs.	8 yrs.	4 yrs.	8 yrs.	1 yr.	4 yrs.	8 yrs.
Genome	*TD*	10.8 a	11.1 a	9.4 a	11.2 a	28.5 a	43.7 a	35.2 a	56.7 a	88	63	37
	DD	10.9 a	12.5 a	8.9 a	11.7 a	25.0 a	50.2 a	30.5 a	66.3 a	89	69	64
Statistical values	*f*	0.06	2.7	1.39	0.23	0.91	0.34	0.82	0.35			
	p	0.8	0.1	0.24	0.64	0.34	0.56	0.37	0.55			
	$MSD_{\alpha\ =\ 0.05}$	0.9	1.7	1.1	2.3	7.4	21.9	10.1	31.8			
	CV	13.2	17.1	21.7	24.1	48.9	53.8	54.1	59.2			

Means with the same letter within a column are not significantly different.
$MSD_{\alpha=0.05}$: Minimum significant difference at α = 0.05.
CV: Coefficient of variation.

would justify the added fertilizer costs and lead to a higher cost-effectiveness would be a worthwhile effort but fertilization after yr-4 would not be recommended. Differences in nutrient use efficiencies and how the efficiencies relate to the availability of nutrients have been observed among purpose-grown species (Aubrey et al., 2012), and such differences can be expected among poplar clones and genotypes. Hence, clonal selection of poplars could benefit from the resource efficiency studies.

5. Conclusion

Our goal was to assess if the same clones would be selected as the most-suited for shorter-term and longer-term stand objectives at a site. Although most tree mortalities occurred before the age of four years, considerable reductions in survival could occur in some clones beyond the establishment phase. In addition, increased mortality as stands age may support selection and utilization of genotypes for shorter rotations. In terms of growth, the unsuitability of some clones was evident at early age while other clones were increasingly less suitable with stand age. Clones with the highest survival were not necessarily the greatest-biomass producers and several clones with lower survival were the best overall biomass producers. Clonal productivity differences were more significant with age and biomass rankings changed between the shorter (yr-4) and longer (yr-8) rotations with only four of the top-ten clones of year-four in the top-ten of year-eight and three clones of the top-ten clones of year-eight also in the top-ten of year-four. Clones belonging to both TD and DD genotypes were affected by wood infection (Septoria) and scars indicating that poplar selection based on disease resistance should be performed at clonal level. Finally, for productivity-oriented stands, site-suitable clones should be selected by productivity first, then narrowed by survival and rotation length. Changes in the most 'site-suitable' clones can be expected between longer and shorter rotations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2019.117670.

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