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Productivity and Biomass Properties of Poplar Clones Managed in Short-Rotation Culture as a Potential Fuelwood Source in Georgia

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Abstract: Georgian forests are very valuable natural resources, but due to the lack of affordable alternatives to firewood, people are forced to use forest resources illegally and unsustainably. The aim of this study was to determine the productivity and biomass properties of four poplar clones from *Aigeiros* and *Tacamahaca* and one control clone, considering their wood and bark characteristics and their proportion in the stems. Short-rotation woody crops with these clones represent a potential source of commercial fuelwood production in Georgia as an alternative to natural forests. These tree characteristics were evaluated after three years of growth. The survival of the clones was generally high. No significant differences in biomass production (dry matter, DM) were found among the four clones tested (DM of approximately 4 Mg ha⁻¹ yr⁻¹), while the control clone achieved significantly lower values for DM. The biomass specific density was exceptionally high, at 481–588 kg m⁻³, which was a result of the high proportion of bark mass in the stem (23.3–37.7%), with a density almost twice that of wood. On the other hand, the tested clones had a very high ash content in the biomass (2.6–4.5%), which negatively affected their energy potential expressed as a lower heating value (17,642–17,849 J g⁻¹). Our preliminary results indicated that both the quantity and quality of biomass are important factors to justify the investment in an intensive poplar culture. The four clones should be further considered for commercial biomass production and tested at different sites in Georgia to evaluate the genotype-by-environment interactions and identify the site conditions required to justify such an investment.

Keywords: poplar; clone; biomass properties; mean annual increment; specific density; bark; wood; heating value; AF8

1. Introduction

Forests in Georgia occupy about 40% of the country's territory [1]. They are exceptionally valuable natural resources at both the regional and global level [1,2]. The forest ecosystems surviving in the mountain massifs of the Georgian Caucasus are the last untouched ("virgin") forests in the temperate climate zone of the Earth [3]. As much as 95–98% of Georgian forests are of natural origin [1], and almost all of them are still naturally regenerated [2]. The species composition, structural diversity, and other characteristics of Georgian forests shape their rich biodiversity, with approximately 400 occurring tree and

shrub species, including 61 species that are exclusively endemic to Georgia and a further 43 to the Caucasus [1].

However, Georgian forests not only conserve their unique biodiversity and perform a variety of important protective functions (100% of the forests are protective forests), but they also ensure the continuous supply of vital direct and indirect benefits and resources to the population [1]. Georgia lies within two “biodiversity hotspots”—the Caucasus and Irano-Anatolia—out of the 36 “biodiversity hotspots” identified by Conservation International as both outstanding and highly threatened areas [4]. The high level of poverty in rural areas, lack of affordable alternatives to firewood, and lack of alternative grazing land force people to exploit forests illegally and unsustainably [5]. The National Forest Agency allocates 600,000 m³ of firewood resources annually, which only meets 25% of the demand for firewood [5]. The rest of the residents are forced to obtain the necessary 1,800,000 m³ of firewood illegally [5]. In addition, public institutions and the private sector also consume a large amount of firewood [5]. Therefore, the scale of logging far exceeds the rate of natural growth of forests located near human settlements. As a result, these forests have been devastated, and it has become necessary to find alternative energy sources for the country to reduce the pressure on natural forests [6].

Eliminating the fuelwood deficit is a complex problem that needs to be solved in conjunction with improved forest, environmental, energy, social, and regional development policies [5]. Energy efficiency is crucial to achieving social and environmental sustainability, economic performance, and energy security [7,8]. The Georgian energy system is in active development, and reforms are influenced in particular by the Association Agreement, signed with the European Union (EU), and by membership in the Energy Community. In the framework of the Association Agreement, Georgia has committed to the implementation of EU directives in the energy sector and will have to comply with the requirements of the Third Energy Package [9]. Among EU member states, solid biofuels have been the most important renewable energy source so far, reaching a share of 40.3% in the structure of primary energy production from renewable sources in 2018 [10]. Solid biofuels are mainly derived from woody biomass from forestry and agricultural crops [11]. Another promising biomass source in Europe includes short-rotation woody crops (SRWC), which are based on short cycles and use genetically superior planting material [12–14].

In this context, short-rotation woody crop (SRWC) plantations with fast-growing tree species seem to be a good alternative to obtain additional biomass for firewood for Georgia. The production of biomass as a raw material for energy production from SRWC plantations is still developing in many countries in Europe and North America [8–20]. Biomass is generally considered carbon-neutral, assuming that emissions from biomass combustion are offset by plant regrowth [21–23]. If biomass resources are available and located close to settlements, biomass disposal and transportation costs remain low, ensuring energy sustainability [8]. In addition, the cultivation of woody biomass resources in the vicinity where they are consumed creates employment in rural areas, which is much needed to maintain the population in small rural settlements [24]. Therefore, biomass from SRWCs is worth considering in order to achieve the goal of developing a more sustainable energy supply and biodiversity conservation in the country [6].

SRWC plantations for bioenergy purposes are a novelty in Georgia and require a preliminary study and elaboration of the basis for the development of plantation management and, in particular, species and clone selection. The use of the best adapted genetic material in the development of plantations contributes to the efficient use of site resources and thus to a higher level of production [25].

Poplar (*Populus* L., *Salicaceae* Mirb.), as a fast-growing tree and the most widely distributed genus in the Northern Hemisphere, provides an excellent opportunity for the selection of natural genetic resources to maximize biomass production in SRWC plantations. This natural genetic diversity of different poplar species occurs in very wide ranges and amplitudes of ecological conditions. When natural easy hybridization between poplar species is also considered, the desirable characteristics of different species can be combined

in breeding programs [26]. In general, most poplar breeding programs aim to develop new genotypes to achieve higher production, greater tolerance to pests and diseases, and specific wood quality [25,27–29]. When considering biomass as an energy feedstock, important energy-related characteristics of interest include a favorable wood-to-bark ratio, high specific gravity (density) [30,31], and heating value [32–34], as well as a low ash/residue content [33] and porosity [35]. In general, despite the fact that some studies have shown that the heating value of bark is comparable to that of wood [36], in SRWC biomass, the proportion of bark mass to total harvested biomass is nevertheless considered negative. Since most minerals taken up by trees are accumulated in the bark, the ash mass fraction in the whole tree is predominantly associated with the bark fraction [37]. Therefore, the energy analysis of tree stems should be carried out considering the properties of wood and bark and their proportion in stems. These properties are influenced by several factors, including stem diameter, changes in cambium with age, genetic control, and environmental factors [37]. Previous studies [34,36–41] on the clonal variation of many of these traits in hybrid poplars and other species of the *Salicaceae* family (willow) have reported a considerable variation in the bark-to-wood ratio and ash mass fraction, a moderate variation in specific density, and little variation in heating value.

Superior poplar genotypes from *Aigeiros* (e.g., *Populus nigra*, *Populus deltoides*) and *Tacamahaca* (e.g., *Populus trichocarpa*, *Populus maximowiczii*, *Populus balsamifera*) sections are the most commonly planted in Europe and potentially the most promising in terms of biomass production for energy purposes in Georgia. Therefore, the aim of our preliminary study was to determine the productivity and biomass characteristics considering the wood and bark properties and their proportion in the stems of five poplar clones from the *Aigeiros* and *Tacamahaca* sections as a potential source of commercial fuelwood production in Georgia.

2. Materials and Methods

2.1. Experimental Location, Soil, and Climatic Condition

The experiment was established in eastern Georgia in the Mtskheta Municipality (41°55′01.75 N 44°46′18.37 E, 586 m a.s.l.) in the village Jighaura, on the right bank of the Tezami River, in the spring of 2017 (Figure 1). The long-term annual mean temperature is 11.89 °C, while the annual precipitation is 632.45 mm. The annual water balance (precipitation minus potential evapotranspiration) of the study site amounts to −410.81 mm. The detailed bioclimatic characteristics of the study site are presented in Table 1 [42].

Table 1. Bioclimatic characteristics of the study site in Jighaura (eastern Georgia) according to the EuMedClim database [42].

Climatic Variable (Unit)	Value
Annual mean temperature (°C)	11.89
Mean diurnal temperature range (°C)	11.02
Maximal temperature of the warmest month (°C)	29.59
Minimal temperature of the coldest month (°C)	−4.50
Annual precipitation (mm)	632.45
Precipitation of the wettest month (mm)	101.03
Precipitation of the driest month (mm)	22.84
Winter mean temperature (December, January, February; °C)	1.11
Summer mean temperature (June, July, August; °C)	22.46
Winter precipitation (December, January, February; mm)	81.65
Summer precipitation (June, July, August; mm)	195.19
Annual potential evapotranspiration (mm)	1048.41
Annual water balance (precipitation minus potential evapotranspiration; mm)	−410.81
Minimal monthly water balance (mm)	−117.15
Maximal monthly water balance (mm)	21.73



Figure 1. The location of the study site in Georgia ($41^{\circ}55'01.75$ N $44^{\circ}46'18.37$ E, 586 m a.s.l.).

The soil type of the experimental plot belongs to Fluvisols according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015), which was developed based on river deposits and correlated with the national classification as an alluvial soil azonal type [43]. Fluvisols generally have low production and are used as cropland or hay meadows [43]. A soil survey conducted prior to the establishment of the experiment revealed that the soil was characterized by a very low organic matter content (less than 2% in the humic horizon), moderate alkalinity (pH 8), silty clay texture, and high stoniness index. The soil was poor in available phosphorus, rich in potassium, and had a high calcium carbonate content that increased with depth [44]. In winter 2017, the soil was plowed to a depth of 30–40 cm and superficially flattened before planting.

2.2. Planting Material and Study Design

The trial was established in early spring in 2017 using 22 cm long-dormant hardwood cuttings that had previously been soaked in water for 24 h to promote rooting.

The genetic material consisted of five clones. Three clones, 89.M.061, 89.M.004, and Kocabey (TR—77/10), were obtained from the Poplar and Fast Growing Forest Trees Research Institute, PFGFTRI in Izmit, Turkey. AF8 is a commercial clone suitable for short-rotation plantations produced by Alasia Franco Vivai in Italy (12030 Cavallermaggiore (CN)), while *Populus pyramidalis* Roz (syn. *Populus nigra* “Italica”, *P. italica* Moench., *P. fastigiata* Desf.) was used as a control. We continue to refer to the name *P. pyramidalis* for consistency. The species was imported from Italy in the last century and showed good adaptability in Georgia. Detailed information about the genetic material used in this study is presented in Table 2.

Twenty cuttings from each poplar clone were used for planting. The cuttings were planted in a completely randomized design with a spacing of 2.0 m between rows and 0.4 m within rows, resulting in a density of 12,500 cuttings per hectare. No mineral fertilizers were used, while an optimal irrigation regime was applied to mitigate the water deficit. Manual weeding was carried out as required during the growing seasons.

Table 2. Poplar clones used in the experiment in eastern Georgia.

Name	Source	Parentage	Sex
89.M.061	PFGFTRI	<i>P. deltoides</i> × <i>P. deltoides</i>	♀
89.M.004	PFGFTRI	<i>P. deltoides</i> × <i>P. deltoides</i>	♀
Kocabey (TR—77/10)	PFGFTRI	<i>P. nigra</i> L.	♀
AF8	Alasia Company	<i>P. generosa</i> 103-86 × <i>P. trichocarpa</i> PEE	♀
<i>P. pyramidalis</i> (control)	Georgia	<i>P. pyramidalis</i>	♀

2.3. Measurement of Tree Characteristics

After three years of growth, the height and diameter at breast height (DBH; measured at a height of 1.3 m) of all trees were measured. DBH was measured using a digital caliper (Mitutoyo, type CD -15DC, UK), while tree height was measured using a calibrated pole. The survival rate was determined by the number of living trees. Aboveground biomass (dry mass, DM) production was calculated using an allometric function commonly used in tree biomass and volume modeling [45]:

$$\log_{10}(\text{DM}) = \beta_0 + \beta_1 \times \log_{10}(\text{DBH}) + \beta_2 \log_{10}(\text{H}), \quad (1)$$

where DBH is the diameter at breast height; H is the height; and β_0 , β_1 , and β_2 are the parameters of the function ($\beta_0 = -7.31111$, $\beta_1 = -0.402705$, $\beta_2 = 4.33891$, $R^2 = 0.958$). The parameters of the function were fitted based on the aboveground biomass of sample trees taken from each genotype. The sample trees were selected for each poplar clone according to their average height and diameter in the experiment [46]. Immediately after felling, the sample trees were weighted. The two sample discs representing the given clone (discs cut at breast height, 1.3 m) were taken to the laboratory to assess the biomass properties [46,47].

2.4. Biomass Properties

All the properties of stem biomass were analyzed in the Laboratory of Production Technology and Quality Assessment of Biofuels certified by the Polish Center for Accreditation PCA (accreditation number AB1585). Analyses were conducted according to standardized procedures, the required number of replicates, and the required repeatability of the results. Since the parameters of the drying process have a significant impact on the specific density and porosity of the dried material [48], the stem samples of all clones were dried under strictly the same conditions in a laboratory dryer (SLW 115, Pol-Eko, Wodzisław Śląski, Poland) at 105 °C until a constant mass was obtained. Then, the samples were divided into subsamples consisting of bark and wood of a given poplar clone. Based on the mass of bark and wood, the mass fraction (%) of wood S_w and bark S_b in the steam sample was determined. Specific density (SD), as an important physical parameter characterizing the ratio of the mass of a substance to its volume (volume including internal pores), was measured based on a displacement method [33] using a quasi-fluid pycnometer (GeoPyc 1360, Micromeritics Instrument Corp., Norcross, GA, USA). The detailed procedure for SD determination was described in our previous work [33]. Since the solid wood and bark samples consist of the cell walls and cell cavities, which contain air and small amounts of gum and other substances, we also determined their absolute density (AD). AD refers to the density of the material without internal pores. Measurements of AD were taken using helium gas for displacement with a gas pycnometer (AccuPyc II 1340 Micromeritics Instrument Corp., Norcross, GA, USA). Based on SD and AD, the porosity p of the samples was calculated according to the equation:

$$p [\%] = \frac{\text{AD} - \text{SD}}{\text{AD}} \times 100 \quad (2)$$

For the proximate analysis of wood and bark, the samples were prepared according to the EN ISO 14 780:2017 standard [49]. The samples (of wood and bark) were ground to a particle size of <1 mm in a laboratory mill (PX-MFC 90D Polymix, Kinematika,

Lucerne, Switzerland). Subsequently, the determination of the ash mass fraction A_d was performed according to EN ISO 18122:2015 [50] in the muffle furnace (FCF 7SM Czylok, Jastrzbie-Zdrój, Poland) and the heating value according to EN ISO 18125:2017 [51] using a calorimeter (IKA C6000, IKA-Werke, Staufen, Germany). The heating value, also called the calorific value, of the biomass was defined by the higher heating value (HHV) and lower heating value (LHV). The HHV is essentially the energy content on a dry basis and indicates the maximum amount of heat that a material can produce when burnt completely [52]. Unlike HHV, the LHV takes into account energy losses, such as the energy used to vaporize water [52]. The difference between these values is practically constant when converted to the dry state and depends mainly on the hydrogen content in the fuel [53]. Therefore, we report both values while in the statistical analysis, and in the following, we refer only to the LHV since this value is more applicable in practice.

The relative self-ignition temperature (TSI) of the samples was determined according to the guidelines of Commission Regulation (EC) No. 440/2008 [54]. The TSI determination was carried out in the temperature-programmed laboratory oven (FCF 2R/TZ-BM Czylok, Jastrzbie-Zdrój, Poland). The test was performed until the sample temperature reached 400 °C, then the TSI was calculated. Details of the procedure are described elsewhere [31]. The synthetic information about the methods, standards, and equipment used for the assessment of biomass quality parameters followed by the repeatability and errors of the measurements are presented in Table 3.

Table 3. Standards followed for biomass quality parameters and analytical equipment used with information on measurement accuracy.

Parameter	Standard/Method	Equipment	Required Repeatability	Reached Repeatability	Standard Deviation
SD	quasi-fluid method	Pycnometer GeoPyc 1360	Not defined	-	0.02
AD	gas method using helium	Pycnometer AccuPyc II 1340	Not defined	-	0.03
A_d	EN ISO 18122	muffle furnace Czylok FCF 7SM	$A < 1\%$ —0.1% absolute $A > 1\%$ —10% relative	Max. 0.06%	
HV	EN ISO 18125	calorimeter IKA C6000	120 J g ⁻¹	Max. 98 J g ⁻¹	
TSI	Commission Regulation (EC) No. 440/2008	laboratory oven Czylok FCF 2R/TZ-BM	Not defined	-	3.2

SD, specific density; AD, absolute density; A_d , ash mass fraction; HV, heating value; TSI, self-ignition temperature.

2.5. Statistical Analysis

To test for variation among the examined clones in terms of mean growth and biomass traits, linear models were implemented. The mathematical model for the single-factor completely randomized design was applied for growth traits (DBH, H, DM), which was appropriate with the study layout:

$$x_{ij} = \mu + \alpha_i + \varepsilon_{ij}, \quad (3)$$

where x_{ij} is the dependent variable, μ is the mean, α_i is the effect of clone i , and ε_{ij} is the random error.

Meanwhile, linear models with the interaction effect were applied to assess differences in the biomass properties (SD, A_d , LHV, p). In the latter analysis, we considered the effect of clone, material (bark, wood), and interaction between the clone and material:

$$x_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk}, \quad (4)$$

where x_{ijk} is the dependent variable, μ is the mean, α_i is the effect of clone i , β_j is the effect of material j , $(\alpha\beta)_{ij}$ is the effect of interaction between clone i and material j , and ε_{ijk} is the random error.

Generally, the analyses for biomass properties were performed separately for wood and bark characteristics; however, since it was unlikely that the feedstock would be de-

barked in commercial operations, we also calculated the average values for stem characteristics as a weighted average of the wood and bark content in the stem.

When the ANOVA indicated a significant effect ($p \leq 0.05$), post hoc comparisons between clones, materials, or interactions between clone and material were performed using a least significant difference (LSD) test.

Pearson correlation coefficients were used to test the relationships between the measured characteristics, while principal component analysis (PCA) was used to further explore the variation and determine patterns in the dataset. In the PCA, the multidimensional space was reduced to eigenvectors (the principal components) corresponding to the eigenvalues that explained the largest part of the variation in the dataset. In this analysis, the eigenvectors were calculated based on the constructed correlation matrix. All the statistical analyses were performed with Statistica (data analysis software system), version 13 [55].

3. Results

3.1. Survival and Growth Parameters of Clones

The survival rate of the poplar clones was generally high. Clone 89.M.061 had the lowest survival rate among the tested genotypes (90%), while two clones, Kocabey and AF8, recorded a 100% survival rate at the age of three. The average diameters of the various genotypes were statistically significantly different ($p < 0.05$). Clone 89.M.061 had the highest mean DBH value (28.4 mm), which was significantly greater than the DBH values of all the other clones ($p < 0.05$ in the LSD test, Figure 2a). In contrast, the control clone of *P. pyramidalis* had the lowest DBH, at 11.6 mm, which was almost 2.5-fold smaller than for the thickest clone.

The heights of trees of various clones were not as diverse as in the case of DBH values. The four tested clones differed significantly in height (298.6–320.1 cm) from *P. pyramidalis*, which produced the shortest trees (200.3 cm; $p < 0.05$ in the LSD test, Figure 2b).

The dry biomass, estimated on the basis of the allometric equation, showed significant differences among clones. Biomass production data were calculated on an area basis, taking into account the survival rate, and did not show statistically different results for the three clones: 89.M.004, AF8, and Kocabey. The 89.M.061 had a slightly lower biomass production but did not considerably differ from that of Kocabey. The largest difference in DM productivity was exhibited between the tested clones and control ($p < 0.05$ in the LSD test, Figure 2c). The mean annual increment (MAI) of dry mass reflected the results for DM per ha and ranged between 2.96 (89.M.061) and 4.14 Mg ha⁻¹ yr⁻¹ (89.M.004). In contrast, the MAI produced by the *P. pyramidalis* achieved a value of 0.78 Mg ha⁻¹ yr⁻¹ (Figure 2d).

3.2. Biomass Properties

All the biomass properties were generally influenced by the wood-to-bark ratio in the stem. The proportion of bark in the stem of the different clones varied from 23.3% in Kocabey to 37.7% in *P. pyramidalis* (Table 4). Overall, the specific density of stem biomass (wood and bark) was high and ranged from 481 kg m⁻³ (89.M.061) to 588 kg m⁻³ (AF8). There were significant differences ($p < 0.05$) between the wood and bark SD (Figure 3). The wood density was 422 kg m⁻³, while the bark density was almost twice as high, at 817 kg m⁻³. Therefore, the bark content resulted in higher mean density values in the clones with a greater ratio of bark to wood in the stem, e.g., *P. pyramidalis*. These results were in contrast to porosity, which was lowest for the biomass of clone AF8 and highest for that of 89.M.061. The mean porosity obtained for wood was 71.1%, and for bark it was 43.7%. The obtained results for porosity were significantly different between these two components of the stem. The ash mass fraction in the stem biomass was generally high and ranged from 2.6% to 4.5%. The lowest ash mass fraction was observed in the biomass of AF8 and gradually increased with the biomass of the Turkish clones until it reached the level of *P. pyramidalis*, which had the highest ash mass fraction. Similarly to density, the ash mass fraction was considerably higher in the bark (9.5%) than in the wood (1.1%).

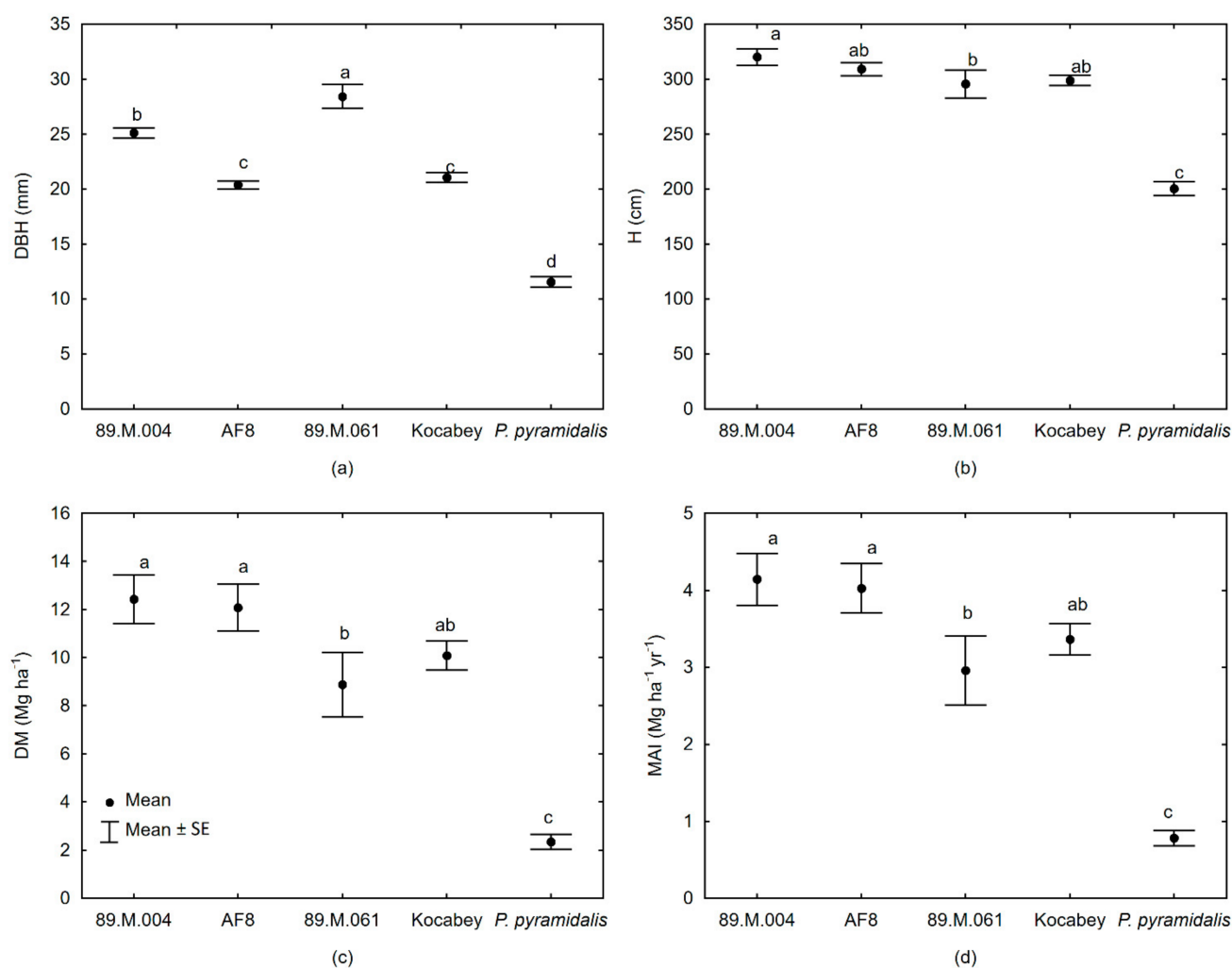


Figure 2. Mean values \pm standard error (vertical bar) for: (a) diameter at breast height (DBH (mm)), (b) height (H (cm)), (c) dry matter yield per unit area (DM (Mg ha⁻¹)), (d) mean annual increment of dry matter yield (MAI (Mg ha⁻¹ yr⁻¹)) for clones. The values expressed per unit area were calculated, taking survival rate into account. The same letters indicate statistically homogenous groups of clones at $p < 0.05$ in the LSD test.

Table 4. Weighted mean values of the stem parameters for the tested clones.

Clone	Sw (%)	Sb (%)	A _d (%)	HHV (J g ⁻¹)	LHV (J g ⁻¹)	TSI (°C)	SD (kg m ⁻³)
89.M.004	71.8	28.2	3.1	18,997	17,708	238	507
89.M.061	75.1	24.9	3.7	19,050	17,758	232	481
AF8	74.4	25.6	2.6	19,103	17,849	245	588
Kocabey	76.7	23.3	3.1	18,985	17,716	244	522
<i>P. pyramidalis</i>	62.3	37.7	4.5	18,922	17,642	236	572

Sw, wood mass fraction; Sb, bark mass fraction; A_d, ash mass fraction; HHV, higher heating value; LHV, lower heating value; TSI, self-ignition temperature; SD, specific density.

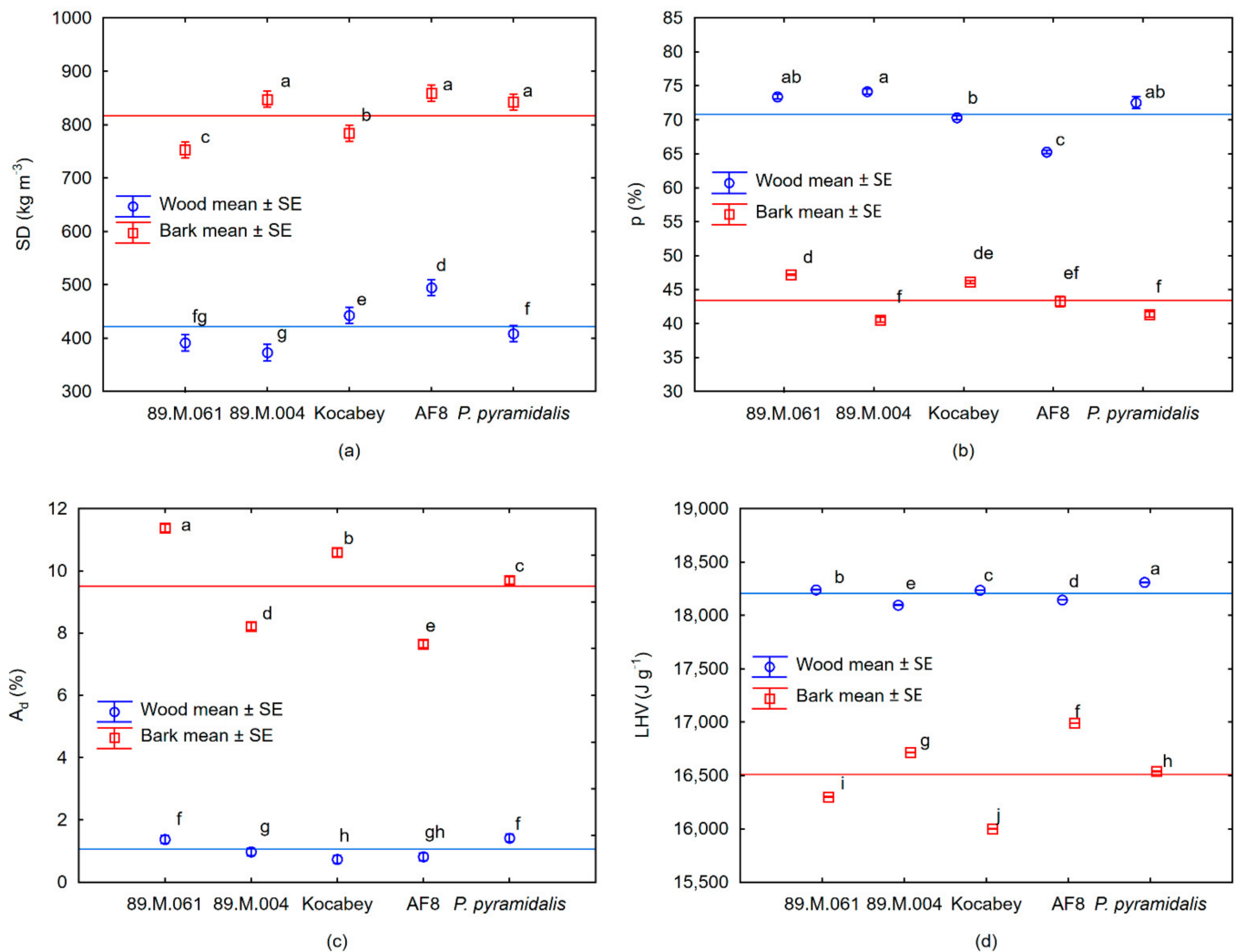


Figure 3. Mean values \pm standard error (vertical bar) of wood and bark for: (a) specific density (SD (kg m^{-3})), (b) porosity (p (%)), (c) ash content (A_d (%)), (d) low heating value (LHV (J g^{-1})). The same letters indicate statistically homogenous groups of clones at $p < 0.05$ in the LSD test.

The highest HHV among all the tested clones was achieved by the clone AF8 ($19,103 \text{ J g}^{-1}$), while the lowest was achieved by *P. pyramidalis* ($18,922 \text{ J g}^{-1}$). The LHV results were in agreement with the values obtained for the HHV of the clones and ranged from $17,642 \text{ J g}^{-1}$ (*P. pyramidalis*) to $17,849 \text{ J g}^{-1}$ (AF8). In general, wood was characterized by a significantly higher LHV ($18,205 \text{ J g}^{-1}$) than bark ($16,508 \text{ J g}^{-1}$). The overall mean values for clones are presented in Table 4, while the detailed data on all the biomass characteristics obtained with the LSD test are shown in Figure 3.

3.3. Relationship between Traits

The Pearson correlation coefficients showed that the tree height (H) was strongly and positively correlated with DBH, while strong negative correlations were observed between H and bark share (Sb) or ash mass fraction (A_d). Similarly, DBH was negatively correlated with Sb and specific density (SD). The correlation matrix also showed that the trees with a high bark mass fraction in the stem had a higher ash mass fraction, which also negatively affected the heating value (LHV; HHV was excluded from the analysis as explained in Materials and Methods). Table 5 summarizes the correlation coefficients between the studied traits. Wood mass fraction and porosity were removed from the analysis because they are the converse of bark mass fraction and specific density, respectively.

Table 5. Correlation coefficients between the studied traits. Blue tones indicate a positive correlation, and red tones a negative relationship.

	Height (cm)	DBH (mm)	Survival (%)	Sb (%)	A _d (%)	LHV (J g ⁻¹)	TSI (°C)
DBH (mm)	0.82	1.00	-0.39	-0.77	-0.42	0.45	-0.22
Survival (%)	0.17	-0.39	1.00	-0.20	-0.63	0.29	0.98
Sb (%)	-0.88	-0.77	-0.20	1.00	0.73	-0.66	-0.36
A _d (%)	-0.86	-0.42	-0.63	0.73	1.00	-0.72	-0.76
LHV (J g ⁻¹)	0.66	0.45	0.29	-0.66	-0.72	1.00	0.44
TSI (°C)	0.34	-0.22	0.98	-0.36	-0.76	0.44	1.00
SD (kg m ⁻³)	-0.42	-0.79	0.63	0.45	-0.08	0.17	0.56

Sb, bark mass fraction; A_d, ash mass fraction; LHV, lower heating value; TSI, self-ignition temperature; SD, specific density.

The results of the PCA are shown in Table 6 and Figure 4. The eigenvalues calculated, based on the correlation matrix, showed the dominance of the first principal component, which explained 52.52% (eigenvalue = 4.2) of the variance and was mainly associated with H, Sb, A_d, and LHV, while the second PC was mainly associated with DBH, S, TSI, and SD, and explained another 37.63% (eigenvalue = 3.0) of the variance. Overall, the first two components explained a large part of the variance, amounting to 90.15%

Table 6. Pearson correlation coefficients between traits and the principal components (PC1, PC2).

Trait	PC1	PC2
Height	0.93	-0.29
DBH	0.64	-0.77
Survival	0.44	0.86
Sb	-0.91	0.28
A _d	-0.95	-0.24
LHV	0.79	0.10
TSI	0.60	0.77
SD	-0.15	0.92

Sb, bark mass fraction; A_d, ash mass fraction; LHV, lower heating value; TSI, self-ignition temperature; SD, specific density.

The locations of the clones in the PCA ordination space showed very different patterns in terms of growth and biomass properties (Figure 1). Generally, however, clones AF8 and in laser extend Kocabey demonstrated a higher survival rate, TSI, and heating value, with a lower ash mass fraction. The 89.M.004 clone demonstrated high DBH and H but a lower SD. Clone 89.M.061 had, desirable, a high DBH but also a higher ash mass fraction and lower SD than the other clones. The reference clone *P. pyramidalis* was distinguished by showing the lowest productivity traits (DBH and H) and the highest share of bark in the stem among all the selected clones, as well as a greater ash mass fraction and specific density.

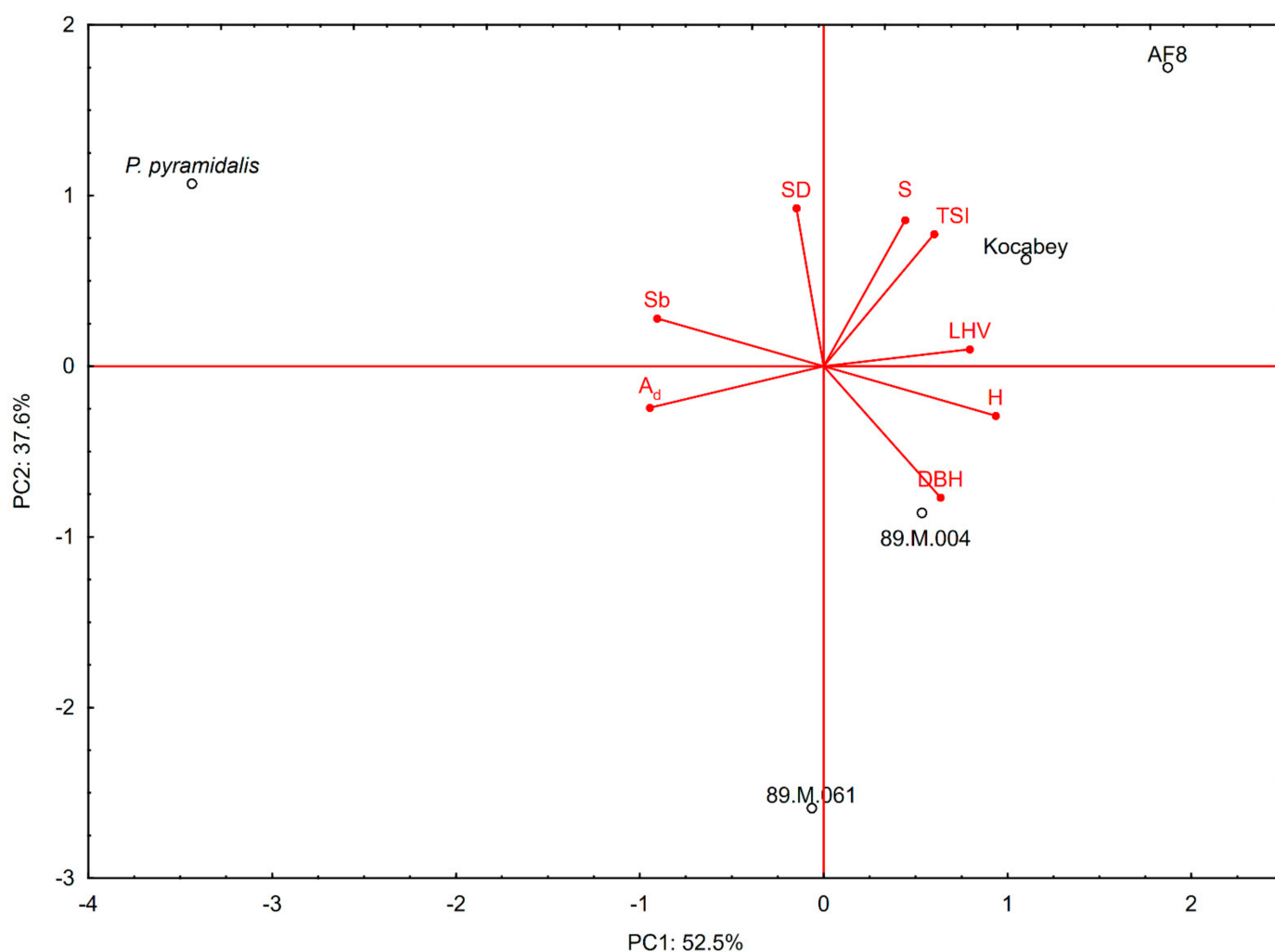


Figure 4. Principal component analysis (PCA) plot showing the multivariate variation poplar clones for productivity and biomass characteristics. Vectors indicate the direction and strength of each variable to the overall distribution. S, survival; TSI, self-ignition temperature; LHV, lower heating value; H, height; DBH, diameter at breast height; A_d , ash mass fraction; Sb, bark mass fraction; SD, specific density.

4. Discussion

High biomass production in SRWC plantations depends on an optimum combination of climatic and soil physical conditions, the availability of moisture during the growing season, the availability of nutrients, the aeration of the soil and suitable species, and clone selection [12]. Thus, the highest yields of 20–25 Mg ha⁻¹ yr⁻¹ are expected to be achieved under suitable climatic conditions, with additional optimization of soil fertility and moisture through fertilization and irrigation. Geographically, most records of the highest productivity of poplars in SRWCs are reported from southern Europe [56–59] and more southern locations in North America [60–62]. The results of several studies also highlight the notable role of clone selection by showing large differences in productivity between clones under the same culture, which can range from less than 1 to more than 25 Mg ha⁻¹ yr⁻¹ [63,64].

This study showed a relatively uniform level of biomass production among the tested poplar clones at the study site in eastern Georgia. The only exception was the control, *P. pyramidalis*, which differed significantly from all other clones in terms of biometric traits and achieved the lowest growth parameters. During the three-year period of our study, the highest DBH was achieved by clone 89.M.061, while the highest trees were produced by 89.M.004. The highest biomass production (DM) was achieved by the two clones, 89.M.004

followed by AF8. However, the MAI for these clones was not high and amounted to approximately $4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. The following two clones, Kocabay and 89.M.061, were characterized by an MAI at a level of about $3 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. The lowest MAI was produced by the control clone *P. pyramidalis* (below $1 \text{ Mg ha}^{-1} \text{ yr}^{-1}$).

Previous studies in the Black Sea region—with similar climatic conditions to those in our study site—showed the high potential (promising results) of all Turkish clones investigated in this study. They were all characterized by significantly higher biomass production than the control clones at the experimental sites established in central Anatolia, south-east Anatolia, and east Anatolia [20]. The black poplar clone Kocabey, native to the region, was already registered by the National Poplar Commission (Turkey), while 89.M.004 achieved an MAI of $62 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in first-stage clone trials in the Black Sea region [20]. The MAI produced by 89.M.004 was more than twice that of the control clone and can be roughly converted to an MAI of DM of approximately $24 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. Similarly, the AF8 clone has shown a high biomass production in many trials and in commercial plantations in the Mediterranean region, with an MAI of about $19\text{--}24 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ [25,32,65]. The low productivity of the investigated clones in the current study may, therefore, suggest unsuitable growth conditions.

Optimal growth conditions for hybrid poplar cultivation have been studied extensively in Italy [65]. According to these studies, the optimal annual average temperature may be in a wide range from 8.5 to $17 \text{ }^\circ\text{C}$, with summer precipitation of $100\text{--}150 \text{ mm}$. These ranges of climatic parameters indicate that our study site falls within limits for optimal climatic conditions. Regarding soil properties, a suitable soil pH for short-rotation poplar cultivation should fall within the range of 5.5 to 7.5 . Soils with either a highly acidic or alkaline pH or poorly or excessively drained; infertile; stony; shallow; or degraded by erosion, compaction, or salinization reduce the productivity required to achieve satisfactory results in cultivation [12]. Land suitability analyses for SRWC have defined the threshold of potential annual biomass productivity as more than $8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ for suitable land [32,66,67]. The soil conditions at the study site, with a pH of 8 , a low organic matter content, and high stoniness, exceeded suitable soil conditions, resulting in the low productivity of the clones, which was far too low for sustainable biomass production on a commercial scale. In order to obtain reliable results for the productivity of the currently tested clones, we propose that further experimental phases should focus on establishing multiple trials under different site conditions. Further experimental phases would certainly limit the pool of potentially useful sites for poplar cultivation in Georgia but would help to achieve the high productivity required to justify an investment in intensive culture. As a supplementary to the above, we suggest the implementation of soil fertilization.

Regarding the biomass properties, they showed, as expected, a considerable variation between clones in terms of bark-to-wood ratio and ash mass fraction, but also quite a large variation in terms of specific density and porosity and a low variation in the lower heating value.

Specific density is an important parameter in assessing the quality of feedstocks for bioenergy production. High densities give a higher energy output on a volume basis and help to reduce transportation costs [37]. The specific density values for the poplar clones in the experiment were exceptionally high ($481\text{--}588 \text{ kg m}^{-3}$), much higher than the wood densities of the 3-year-old poplar clones in the study of Tharakan et al. ($330\text{--}370 \text{ kg m}^{-3}$) [37] or the 10-year-old poplar clones in continental Canada ($325\text{--}366 \text{ kg m}^{-3}$) [29].

From a biomass production perspective, selecting clones that combine a high wood density with a high volume of growth maximizes the production and energy output on an area basis [37]. Our preliminary results showed that the best combination of productivity and density was achieved for the clone AF8, but all other clones tested in our study were also characterized by a high wood and bark density.

The exceptionally high values of specific densities for biomass raw materials obtained in our study resulted directly from the fact that all the clones were characterized by a

relatively high bark mass fraction in the stem, ranging from 23.3% to 37.7%, with a density almost twice that of wood.

In general, the bark mass fraction results for the sample trees, which reached DBH values of 11–28 mm in our study, were comparable to results obtained in other studies on poplar clones from similar DBH ranges [68]. Bark mass fraction is known to decrease with increasing DBH and age [34,36,68]. As described by Guidi et al. [68] for 2-year-old shoots of *Populus deltoids* L., the bark mass fraction gradually decreased from 35.8% to 7.1% in the 10–90 mm diameter range. The stabilization of bark mass fraction (less than 8%) was visible when shoots reached 60 mm in diameter [68]. In the present study, we also found a clear negative correlation between bark mass fraction and growth traits DBH and H, suggesting that rotation length should be extended if the stabilization of the wood-to-bark ratio is deemed desirable.

Although bark was characterized by a very high SD in our study, it should be emphasized that the bark mass fraction in biomass tends to be considered a negative characteristic of the energy feedstock. Since most of the minerals taken up by trees are accumulated in the bark, the ash content in the whole tree is highly dependent on the bark mass fraction [33]. Consequently, a high ash mass fraction in the biomass feedstock negatively affects the heating value.

The heating value of the biomass as a bioenergy feedstock of the investigated clones was comparable to publications on hybrid poplars [32,33,69], furthermore to the heating value of other tree species [70], and suggested a similar or even better energetic potential compared to waste biomass (bio-waste) from the agri-food industry [8,51,70–72]. As expected, a high variation in the heating value of the biomass of the poplar clones was not detected. The difference in the heating value mainly arose from the different share and composition of bark and wood.

The lower heating value of the tested clones for wood was in the range of 18,100–18,300 J g⁻¹ and was higher than the LHV determined for bark: 16,000–17,000 J g⁻¹. Overall, when considering woody biomass as a bioenergy feedstock according to EN ISO 17225-1:2014 [73], typical LHV values of bark and wood from various tree species are comparable for bark (19,000–19,200 J g⁻¹) and for wood (18,900–19,100 J g⁻¹). However, the range of variation in these values is much larger for bark (17,100–21,300 J g⁻¹) than for wood (18,400–19,800 J g⁻¹) [73]. The bark contains less cellulose and more lignin and extractives than wood [34,74]. For this reason, the quantities of these components relative to the extractives and ash mass fraction of the biomass have an impact on the combustion temperatures and energy potential of the feedstocks [34]. As our results showed, the energy potential of poplar bark decreased with increasing ash mass fraction ($r = -0.72$). The ash content of the bark was notably high, ranging from 7.6% (clone AF8) to 11.4% (clone 89.M.061). According to EN ISO 17225-1:2014 [73], the typical ash content of bark should fall within the range of 0.8–5%, which is consistent with several empirical studies conducted on different tree species [36,37,75–77], although higher values of ash were also found [46,75,78]. Nevertheless, the exceptionally high ash content obtained in the studied poplar clones prompted us to consider the specific factors that influenced these results. It seems likely that this phenomenon can be explained in part by the environmental conditions of the study area. The dry, windy climate may cause mineral dust to be deposited on the bark surface, which is not adequately removed by the low rainfall. As a result, the high ash mass fraction in the bark reduces the energy potential of whole stems. Anderson and Zsuffa [79], in turn, draw attention to the possible presence of a genotype–environment interaction with respect to nutrient availability.

Despite the differences in the LHV and ash content between wood and bark in the present study, the LHVs of whole stems for different clones were comparable and ranged from 17,600 to 17,800 J g⁻¹. The values obtained were lower than the typical value for poplar of 18,400 J g⁻¹ according to EN ISO 17225-1:2014. This result was undoubtedly influenced by the high bark content in the biomass and the high ash content in the bark. In this context, it should be noted that bark fuel contains silicon oxide (SiO₂) and alkali

metals such as potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg), which determine the behavior of ash during combustion. Low melting temperatures can form very “sticky” silicate melts that occur during the combustion process and form deposits on the burner grate [36,75]. Bark can form slag at 850 °C, while the actual combustion process takes place at a temperature of approximately 1100 °C [80]. Therefore, due to the different chemical properties of bark and wood, the bark mass fraction should not be ignored when assessing the overall fuel quality of crops.

Regarding the clones tested, the Kocabey clone had the lowest bark-to-wood ratio, while the most desirable overall biomass properties were obtained by the AF8 clone, which had not only a desirable high wood and bark density but also lower ash content and a higher heating value than all the other clones. Similar to the productivity results, the control clone was characterized by inferior biomass feedstock properties compared to the remaining clones.

5. Conclusions

In this study, the potential biomass yield and biomass energy properties of poplar clones in SRWC under the specific climate and environmental conditions of eastern Georgia were recognized for the first time to contribute to solving the energy deficit in the country. Our preliminary results indicated that both the quantity and quality of biomass are important factors in justifying the investment in an intensive poplar culture. None of the clones tested in this study site had all the desired quantitative and qualitative characteristics, although all four clones tested performed better than the control clone. The productivity of the tested clones at the current stage of the experiment was far too low to justify the investment in intensive culture, while the biomass properties of the tested clones as an energy feedstock were generally slightly below the normalized values. The tested clones had desirable, exceptionally high densities on the one hand and exceptionally high ash content in the biomass, on the other hand, which negatively affected the energy potential of these clones. In addition, we showed that a high bark mass fraction in the stems had a negative effect on the quality of the biomass feedstock for energy purposes. Bark content can be controlled by appropriate clone selection and silvicultural means. To improve biomass as an energy feedstock, we, therefore, propose an extension of the rotation length, which should favor larger stem dimensions and, thus, a lower and more stable bark mass fraction in the stems.

We also pointed out a number of potential difficulties that Georgia will face in preparing to invest in biomass energy plantations. Future research should focus on the currently tested clones, perhaps enriched with commercially available clones that perform well under similar climatic conditions, and test them at multiple sites in Georgia to further identify the potential for genotype-by-environment interactions, which will enable the selection of stable clones for operational use. In addition, it would be beneficial to conduct experiments to analyze the effects of fertilization and irrigation on the growth of poplar clones at different test sites.

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Symbols and Nomenclature

DM	Dry matter
SRWC	Short-rotation woody crop
DBH	Diameter at breast height
H	Height of stem
TSI	Relative self-ignition temperature
A _d	Ash content in dry state
HHV	Higher heating value
LHV	Lower heating value
SD	Specific density
AD	Absolute density
P	Porosity
Sw	Wood mass share in steam
Sb	Bark mass share in steam
LSD	Least significant difference test
PCA	Principal component analysis
MAI	Mean annual increment

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