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Influence of Soil Characteristics on the Growth of Poplar Short Rotation Coppice (SRC) under Suboptimal Conditions

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Abstract – Several studies have discussed the growth of poplar short rotation coppices (SRC). Soil characteristics have a large effect on the yields of sites with no access to surplus water sources – especially on their physical and chemical properties contributing to water storage, all of which limit growth. We conducted our research on a fourth rotation plantation established with two different poplar clones ('AF2' and 'Kopecky') on a site without groundwater in the rooting zone to describe the influence of topography and soil parameters on biomass production. For both hybrids, 5–5 sample areas were planted. Systematic soil sampling, a tree inventory, and a destructive tree survey were completed to provide an equation of site and clone specific biomass estimation. Our results revealed that the shallower, eroded areas presented low-yield patches, particularly when compared to the parts with deeper rooting zones and soil richer in mineral and organic colloids. The amount of the plant available water, pH value, organic matter content, and $CaCO_3$ content have the most significant effect on growth. No meaningful growth difference emerged between the two clones. The previously mentioned soil properties greatly influence tree growth on sites with no direct access to the groundwater; therefore, a detailed site description is indispensable for plantation planting.

short rotation coppice (SRC) plantation / hybrid poplar / soil characteristics / Hungary

Kivonat – Talajtulajdonságok hatása nemesnyáras rövid vágásfordulójú ültetvények növekedésére kedvezőtlen termőhelyen. A nemesnyár rövid vágásfordulójú sarjaztatásos ültetvények növekedését számos korábbi munka vizsgálta. Többletvízhatásól független termőhelyeken felerősödnek a talaj fizikai és kémiai adottságainak vízgazdálkodáson keresztül a növedékre gyakorolt korlátozó hatásai. Egy többletvízhatástól független termőhelyen két nemesnyár fajtán ('AF2' és 'Kopecky') vizsgáltuk, hogy a domborzat és talajtulajdonságok miként befolyásolják a biomasszahozamot. Fajtánként 5–5 mintaterületen végeztünk talajvizsgálatot és faállományfelmérést, hogy az adott területre jellemző becslőfüggvényt szerkeszthessünk. Eredményeink szerint a sekélyebb termőrétegű, erodáltabb területek gyengébb növekedésű termőhelyi foltokat jelentettek, mint a mélyebb termőrétegű, ásványi– és szerves kolloidokban gazdagabb részek. A növekedést leginkább befolyásoló tényező a diszponibilis vízkészlet, pH, illetve a szervesanyag– és mésztartalom. Nincs szignifikáns különbség a fajták növekedése között. Megállapítottuk, hogy – többletvízhatástól független termőhelyen – fenti talajtulajdonságok jelentős hatással bírnak a növekedésre, így a részletes termőhelyfeltárás megkerülhetetlen az ültetvények létesítésének.

rövid vágásfordulójú sarjaztatásos ültetvény / nemesnyár / talajtulajdonságok / Magyarország

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1 INTRODUCTION

The use of renewable energy has risen in Europe in recent decades (IEA 2010, Eurostat 2020). Nevertheless, further steps are required to achieve the ambitious goals set in 2021 (Sikkema et al. 2021). Plantations containing fast-growing tree varieties exist across Europe to provide renewable raw materials for the energy industry. The planted species include mainly poplars (*Populus* spp.) on warmer and less humid sites; willows (*Salix* spp.) on cooler and more humid sites; and black locust (*Robinia pseudoacacia*) on warm and dry sites (Dickmann 2006, Rae et al. 2009, Fischer et al. 2010, Lindegaard et al. 2016, Camia et al. 2018, Oliveira et al. 2020). The shift from fossil fuels to woody energy crops in the power industry is favourable since it can contribute to lowering net CO_2 emissions, which is an important tool to mitigate the effects of climate change.

In addition to biomass production, short rotation coppice (SRC) plantations provide several environmental services (Dimitriou et al. 2011, Zitzmann – Rode 2021) because they create diverse habitats in agricultural systems, filter water, protect soils against erosion, and accumulate carbon below ground over the long term (Meyer et al. 2021). Compared to intensive agricultural use, fast-growing trees – such as poplar or willow hybrids – require little effort to cultivate. In most cases, mechanical weed control is used instead of herbicides; moreover, only in the first years after the establishment or coppicing. Pesticides are used only in insect gradations. Therefore, the plantations are relatively permanent systems that provide undisturbed shelter for animals and suitable habitats for a variety of plant species (Zitzmann – Rode 2021). Compared to agricultural systems, plantations can have a higher effect on the groundwater level with their intense transpiration and interception (Fischer et al. 2013).

In optimal cases, poplar SRC plantations are established on sites with groundwater accessibility or an irrigation system (Bergante et al. 2010) where the trees can use the surplus water during their growth. Precipitation is the only source of water for poplar plantations on suboptimal sites. The water stored in the soil – mostly determined by soil organic matter and soil physical properties – is a crucial factor in determining the potential yields (Salehi – Maleki 2012, Ferré et al. 2021, Heilig et al. 2021). The soil's chemical parameters and nutrient levels also play significant roles (Tufekcioglu et al. 2005, Paris et al. 2011, Netzer et al. 2018). Meteorological conditions greatly affect actual growth (Al Afas et al. 2008), especially with deficient soil water.

Experimental poplar SRC established on irrigated sites or non-irrigated sites affected by groundwater offer excellent opportunities to compare the clonal differences in terms of survival and productivity or to explore the effects of nutrient levels on the growth of the trees (Tufekcioglu et al. 2005, Szabó et al. 2016, González–González 2017, Schlepphorst et al. 2017, Ferré et al. 2021). The studies based on suboptimal sites (Hauk et al. 2014, González–González 2017, Schlepphorst et al. 2017, Niemczyk et al. 2018, Oliveira et al. 2018) can show the performance of the hybrids under stress and help decision-making of plantation management. Most poplar SRC plantations are established on suboptimal sites in Hungary (Kovács et al. 2020). According to our hypothesis, the most important soil characteristics affecting yields on sites with no access to groundwater are those that describe the soil's water retention and the amount of water available to plants.

In addition to site characteristics that affect the survival and the growth of different poplar varieties, the adaptation abilities and growth potential of hybrids can make one more suitable than the others under given conditions and management. Clone comparison trials are a frequent means to choose optimal clone hybrids for different regions, which aids SRC management (Dillen et al. 2013, Nerlich et al. 2016, Shifflett et al. 2016, Landgraf et al. 2020).

This study aims to answer the following research questions: (I) Which soil characteristics define the biomass yield of a poplar SRC established on a site with no groundwater availability? (II) Is there any site gradient that can cause growth heterogeneity over the research area? (III) Which of the two poplar clones shows better growth on a site not connected to the groundwater table? To answer these questions, a digital surface model was analysed, soil auger profile description and sampling were performed in 10 sample areas, and tree parameters were measured after the growing season of 2020.

2 MATERIALS AND METHODS

2.1 Study area and site survey methods

The research plantation was located in the Marcal Basin, in the southern outskirts of the Pápa–Devecser Plain microregion, near the village of Gógánfa (N47°02'03.0", E17°10'38.1"). According to the Köppen–Geiger classification system, the dominant macroclimate of the region was a warm temperate, fully humid, and hot summer climate (Cfa). Halász (2006) reported 10.4 °C as the mean annual air temperature for the microregion in the 1971–2000 period and 17.0 °C for the growing season, while the sum of precipitation was 601 mm throughout the year and 364 in the growing season. The Hungarian National Meteorological Service (Országos Meteorológiai Szolgálat) provided the meteorological data for the last decade (2011–2020). The data originated from the Sümeg meteorological station (N46.96°, E17.29°). The distance between the station and the plantation was 12 km. The annual mean temperature was 11.4 °C and the total precipitation 701 mm, while in the growing season it was 16.4 °C with 445 mm respectively. Spring drought occurred five times during this period, with the last one occurring in 2020 (*Figure 1*). Between 7 March and 27 April 2020 (51 days), 11.1 mm of precipitation was measured; 8.2 mm on 12 April and under 1.5 mm per day for the remaining days. The mean daily temperature increased from 6.5 °C to 11.6 °C (9 days had a lower mean temperature than 5.0 °C). The forestry aridity index (FAI) – introduced by Führer et al. (2011) – over the last 10 years was 6.59, while in 2020 it was 4.77. Lower FAI values represented a colder and more humid climate.

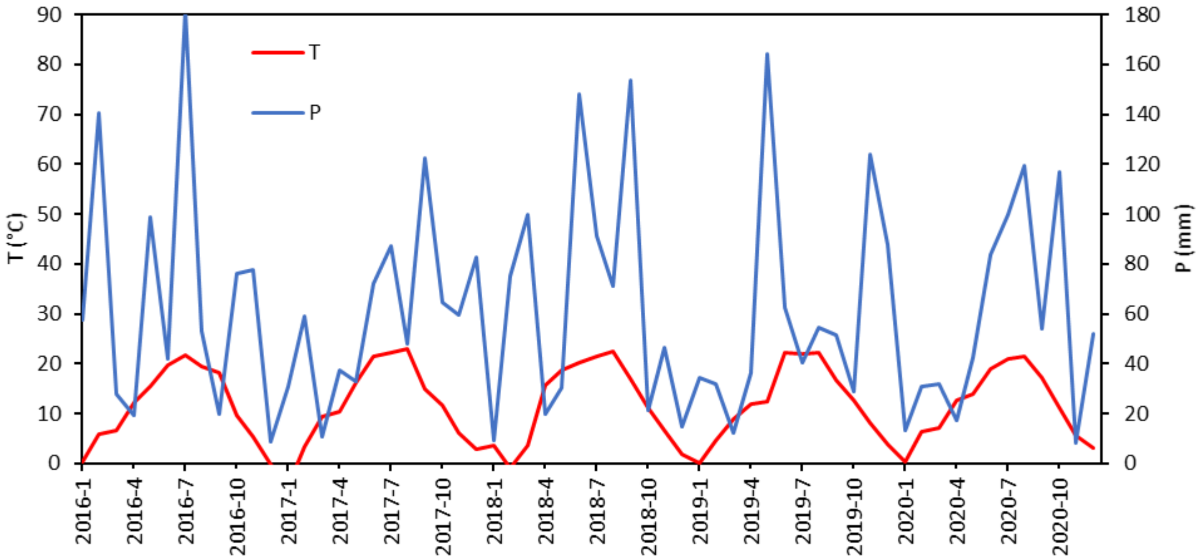

Figure 1. Monthly averages of air temperature (T) and sums of precipitation (P) measured at Sümeg between 2016 and 2020

The research area was on an elevated hillside close to Marcal River, which in recent history has not been affected by floods. The groundwater level lies several meters below the surface. The soils were mostly formed on alluvial sand deposits and partly on sandy loess. There were Fluvic Cambisols and Endocalcaric Luvisols (IUSS Working Group WRB 2015) found with different grades of erosion and with different amounts of gravel across their profiles. Fluvic Cambisols were located in the deeper area of the site and on the top of the hill, where, due to the erosion, loess and other fluvic material were transported and older fluvic material appeared on the surface. Loess could accumulate mixed up with the eroded material on the gentle slopes of the hill.

Ten auger profiles were opened in 2020. The samples were collected systematically from every 30 cm thick layer to a depth of 120 cm or to the heavily compacted gravel deposit layer which is impermeable for poplar roots. The maximum rooting depth was 120 cm, as no roots were found below that depth.

We analysed the soil samples in the laboratory of the University of Sopron. We measured the soil pH in a 1:2.5 soil–distilled water suspension (Motsara – Roy 2008). The determination of soil organic matter content (OM) was based on the Walkley–Black (1934) method. Soil particle size determination was done according to the Köhn pipette method (Motsara – Roy 2008). Gravel was quantified as coarse fragments (CF) in weight percentages (particle size >2.0 mm). Sand (Sa) fraction was between 2.0 mm and 0.05 mm, while the clay fraction (Cl) was under 0.002 mm. Silt (Si) was between the Sa and Cl. We collected undisturbed soil samples with 100 cm^3 cylinder samplers from each layer to measure their bulk density (BD). The layer thicknesses were reduced by the proportion of the CF to obtain the rooting zone depth (RZ). To measure the total $CaCO_3$ content, we employed the Scheibler apparatus and expressed the contents in percentages. Plant available phosphorus content (PAP) was extracted with acidic ammonium lactate solution and the determination of its amount was based on UV/VIS spectrophotometry (Egnér et al. 1960).

To evaluate the soil nutrient levels, we compared them to the categories set up by Buzás (1983). The soils with sand dominated texture were poor in phosphorus when their PAP level was lower than 60 mg kg^{-1}, between 60 mg kg^{-1} and 100 mg kg^{-1} medium and above 100 mg kg^{-1} it was well–supplied.

The further comparisons and analyses were based on the summarised data of the profiles. The reduced layer thicknesses were used as weights to calculate average values of pH and the proportion of soil particle grades (Sa, Si, Cl). Secondly, the total weights of the layers were determined with the use of BD. From these, the absolute amount of nutrients were calculated for every soil profile.

2.2 Description of the SRC plantation and tree measurement methods

The plantation was established on arable land in 2011 in a 3.0 × 0.5 m grid (6 667 trees ha^{-1}). Twenty cm-long cuttings were pushed into the soil with pneumatic machinery after tilling and disc harrowing the soil. Two clones were planted in separate blocks: 'AF2' on 13.5 ha and 'Kopecky' on 7.9 ha. Mechanical weed control (disc harrowing) was done between the rows twice for each growing season.

'Kopecky' was planted on sample areas 1, 2, 3, 5, 8, and 'AF2' was used on sample areas 4, 6, 7, 9, 10. 'Kopecky' (*Populus x canadensis (Moench)* 'Kopecky') was selected as a male clone with straight stems that showed good initial growth. Nevertheless, after 6–8 years, growth decreased. This clone had a medium wood density, and its timber was used for both industry and as an energy source. Halupa – Tóth (1988) recommended it even on suboptimal sites. 'AF2' (*P. x canadensis (Moench)* 'AF2') – a male selection – grew a straight stem. Its growth was good in the initial years, which made this clone suitable for use as energy. It had a low density timber. This clone adapted well to different site conditions, and Vágvölgyi (2014) recommended it for clayey soils and sandy soils.

The harvest cycle was three years long. No harvest data was gathered in 2013. The average yield of 'AF2' was 8.3 dry Mg ha^{-1} in 2016 and 8.0 dry Mg ha^{-1} in 2019 while 'Kopecky' showed lower values: 7.2 dry Mg ha^{-1} in 2016 and 7.1 dry Mg ha^{-1} in 2019. The results of this paper are based on the first growing season of the fourth rotation – measured in November 2020.

Two rows 20 m long were surveyed – with a maximum of 80 stumps close to the soil profiles. Altogether, we evaluated 10 plots. Using a measuring tape with mm accuracy, we measured the breast height circumference (CBH) of every shoot. For measurements under 30 mm CBH, we only recorded the number of shoots. The CBH values were calculated to diameter at breast height (DBH) with a division by π. We paired these values to stumps in every case. The height of the tallest shoot was obtained with a telescopic rod, rounded to10 cm.

To achieve higher precision, we established yield estimation functions for both clones. We sampled trees along the whole DBH distribution – class intervals were 0.318 cm (1.0 cm in CBH) wide. Two trees were felled from the smallest DBH class, two trees from the largest, and one from each class in between. After felling, we measured circumferences along the stem, length (h), and shoot weight (TBM). After drying at 105 °C for three days, samples were weighed (absolute dry weight) and the volume of the samples was determined by submerging them in water. Based on these data, we calculated the density, moisture content, and total dry weight of the sample trees.

2.3 Data procession and statistical analyses

During the preparation of the site survey, we analysed the European digital elevation model (EU–DEM). Version 1.1 had a 25 m by 25 m pixel resolution (Bashfeld – Keim 2011). This raster model was processed in QGIS v 3.14 software (QGIS.org 2020). The contour lines, aspect and slope were determined via built-in functions, and this software also helped visualise the thematic maps.

The statistical analyses such as the calculation of averages, standard error (*SE*), *t*-test, correlation analysis, regression analysis, the performance of principal component analysis (PCA), and the creation of graphs were done in R (R Core Team 2014).

The physical measurements of soils were analysed via the Rosetta Lite v. 1.1 software (Schaap et al. 2001) to calculate the soil's hydraulic parameters to determine its volumetric water content with the van Genuchten (1980) equation. The plant available water content (PAW) was the difference of the water content values at pF4.2 (wilting point) and pF2.5 (field capacity). Two topographical parameters (elevation and aspect) and six soil variables (pH, OM, $CaCO_3$, PAP, PAW, and Sa) were used in PCA to explore environmental gradients. CF, RZ, and BD were not added separately, since they were used in the calculation of the total amount or weighted average of the variables we used. The finer texture fractions (Si+Cl) are omitted since they are complementary classes of sand. The significant axes were used in Pearson's correlation analysis along with the stand parameters to find the relation between soil characteristics and the growth of the stands. The significance values of the multiple comparisons were adjusted via a Bonferroni correction.

Based on the field measurements, logarithmic curves were fitted to the DBH-height data pairs separately for every plot. We calculated the mean DBH as a quadratic mean of the DBH values. The mean height (H) was represented as a weighted average of the height values, and weights were the basal area (G) of the given shoot. The number of trees (N) and their total amount of oven-dry aboveground biomass (DBM) were calculated at hectare levels. To describe the average growing space of a tree (S), the area of the sample areas was divided by the number of stems. The reduction stem numbers (RS) was determined as the difference between the current and planted stumps divided by the number of planted cuttings expressed in percentages. Resprouting capacity (RC) is given as the average number of shoots per stump. The descriptive parameters of the two clones were compared with independent samples *t*-test.

Among tree parameters, DBH had the closest relationship with weight. Therefore, we expected an allometric relationship between DBH and the total dry weight of a tree in the following form:

$$\mathrm{TBM} = \mathrm{a} \times \mathrm{DBH}^{\mathrm{b}}, \tag{1}$$

Where:

TBM:: biomass of a single tree (absolute dry g),
DBH: diameter at breast height (cm),
a, b: parameters.

The results of the destructive sample collecting were used in model building. The fitting of the equations – least squares method – and calculations were made in R software (R Core Team 2014). To evaluate the model performance coefficient of determination (R^2), we calculated root mean square error (*RMSE*) and normalized mean bias (*NMB*). The small shoots (under 30 mm CBH) were put to the equation as stems with DBH = 0.6 cm which is CBH = 1.9 cm, the quadratic mean of the 0.1–3.0 cm CBH range. The H, DBH, and DBM data were relativised to eliminate the clonal differences in the final comparisons. The values were divided by the maximum of the given clone to get the relative H, DBH, and DBM.

3 RESULTS

3.1 Results of site survey

Figure 2 shows the topography of the research site. According to the EU–DEM, the maximum elevation difference was 15 m. The dominant aspect was southwest; it covered more than half of the area. Proportions of the south and west aspects were roughly equal, and together they accounted for about a third of the total area. The rest was southeast aspect with 6% of coverage. Sixty per cent of the area had flat or very gentle slopes (under 2°) and gentle slopes dominated the remaining area (2–5°). Altogether these values represented a gentle hillside pointing mostly to the south; it varied in flat areas.

The soil profiles were aggregated according to their soil group. Endocalcaric Luvisol was found in five cases (profiles: 2, 3, 4, 8, 10). Sandy clay loam texture was dominant within these profiles. The rest (profiles: 1, 5, 6, 7, 9) were described as Fluvic Cambisol. In these cases, the texture was coarser. Altogether it could be characterized as sandy loam (*Table 1*). The fluvic characteristic was shown by the appearance of gravel-rich (ca. 30%) layers between 30 and 90 cm below the surface.

Table 1 contains the average topographical, soil physical and chemical properties of the two soil groups. Generally, the two groups were similar in their suitability for poplar cultivation. However, the Endocalcaric Luvisols showed a slightly better picture. The higher OM and PAW in the soils were more favourable on sites with no groundwater in the RZ. The neutral pH and the low $CaCO_3$ levels were within the optimal range. Both soil groups were medium- or well-supplied in PAP. The soil's physical properties were similar, but Fluvic Cambisols had more Sa and CF; therefore, their BD was higher. Endocalcaric Luvisols were deeper in the sense of RZ and they could store more PAW than the Fluvic Cambisols, but the difference between the groups in the average PAW was small.

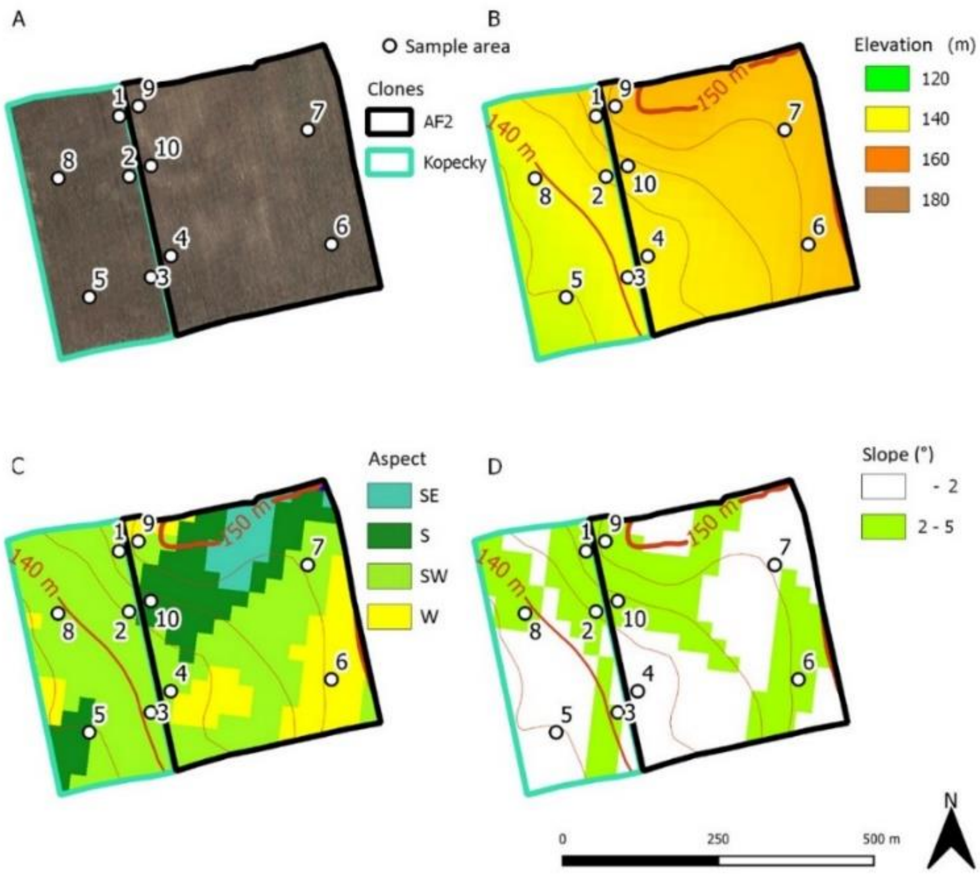

Figure 2. Maps of the research area (A – location of the samples areas, B – elevation map, C – Aspect map, and D – slope map)

Table 1. Means and standard errors (SE) of the topographical, soil physical and chemical properties for the two soil groups (OM – organic matter, PAP – plant available phosphorus, RZ – rooting zone, CF – coarse fragments, BD – soil bulk density, and PAW – plant available water)

Variable	Endocalcaric Luvisol		Fluvic Cambisol	
	Mean	SE	Mean	SE
Elevation (m)	142	0.840	145	2.083
Slope (°)	2.4	0.354	2.4	0.530
pH(H_2O)	7.3	0.108	6.9	0.150
$CaCO_3$ (%)	3.6	0.848	1.3	0.601
OM (%)	0.8	0.070	0.6	0.049
PAP (mg kg^{-1})	132	36.259	130	27.667
RZ (cm)	100	5.757	73	9.088
CF (%)	11	0.713	13	2.145
Sand (%)	61	6.174	73	2.664
Silt (%)	15	3.431	11	0.991
Clay (%)	24	2.820	16	2.542
BD (g cm^{-3})	1.53	0.034	1.72	0.019
PAW (mm dm^{-1})	11	0.762	10	1.562

3.2 Results of the biomass estimation

Nine 'Kopecky' clone trees were felled. Their DBH range was 1.1–3.2 cm, and their heights were between 2.5 and 4.9 m. Their average density was 391 kg m^{-3}. Their moisture content was 48%. Eleven 'AF2' trees were felled. Their DBH ranged from 1.0 to 3.7 cm, and their height was between 2.4 and 5.0 m. Their density was lower, 331 kg m^{-3}, and the average moisture content was 53%.

The functions we developed had high scores of R^2, above 0.98 (*Table 2*). The *RMSE* levels were low, and the 'Kopecky' models fitted better to the dataset, than 'AF2' ones. The *NMB* of height estimation was low and negative for both clones. For TBM models, their *NMB* values were low negative. This indicated a small underestimation in both height and TBM models.

Table 2. Parameters of the height and biomass estimation models (h – tree height (m), DBH – diameter at breast height (cm), a and b – fitted parameters, ln – natural logarithm, R^2 – coefficient of determination, RMSE – root mean square error, NMB – normalized mean bias, and TBM – biomass of a single tree (dry g))

Height model:	h = a × ln(DBH) + b				(2)
Clone	a	b	R^2	RMSE	NMB
'Kopecky'	2.0727	2.0327	0.9877	0.0907	-0.0008
'AF2'	2.0560	2.2864	0.9898	0.0919	-0.0018
Biomass model:	TBM = a × DBH^b				(1)
Clone	a	b	R^2	RMSE	NMB
'Kopecky'	119.6937	2.2797	0.9884	64.1922	-0.0427
'AF2'	89.3915	2.3642	0.9749	114.2968	-1.2769

The variables in *Table 3* were calculated on level sample areas. The average height of 'Kopecky' ranged between 3.8 and 4.2 m. Similar results were shown by 'AF2', which were between 3.8 and 4.1 m. The DBH distribution was the opposite of the H distribution. 'AF2' had higher values of average DBH (1.7 – 2.2 cm) while 'Kopecky' ranged only between 1.1 and 1.7 cm. S showed a similar pattern as DBH, as did N. The overall average of the S and N were almost equal ('Kopecky' – 3.7 m^2 $tree^{-1}$ and 2 933 trees ha^{-1}, 'AF2' – 3.8 m^2 $tree^{-1}$ and 3 167 trees ha^{-1}). The basal area of 'Kopecky' was between 2.7 and 4.1 m^2 ha^{-1} and for 'AF2' was 4.1 and 5.7 m^2 ha^{-1}. This predicted higher values of DBM for 'AF2', which was 8.0 Mg ha^{-1} on average, and for 'Kopecky', it was 7.3 Mg ha^{-1}. The average RS after three harvest cycles was rather high at 54%. The two clones showed similar values; the mean of 'AF2' was 53% and for 'Kopecky' it was 56%. Both extreme values were found at 'AF2' where the minimum RS was 36% while the maximum was 79%. The RC was 5.3 shoots $stump^{-1}$ on average; 'AF2' had a peak of 12 shoots $stump^{-1}$. 'Kopecky had higher values; the average was 5.9, and the highest value was16 shoot $stump^{-1}$.

There is no significant difference between the two clones in most parameters (H, S, N, RS, RC, and DBM). Significant difference is observed in the case of DBH ($t_{(7.980)}$ = 3.127, p = 0.014) and G ($t_{(7.465)}$ = 3.950, p = 0.005).

Table 3. Stand parameters of the sample areas. (H – mean height, DBH – mean diameter at breast height, N – trees over ha, S – growing space of a tree, G – basal area, DBM – oven–dry biomass, RS – Reduction of the number of stems, and RC – resprouting capacity)

Sample area	H (m)	DBH (cm)	N (trees ha^{-1})	S (m^2 $tree^{-1}$)	G (m^2 ha^{-1})	DBM (Mg ha^{-1})	RS (%)	RC (shoot $stump^{-1}$)
1	3.8	1.1	4 167	2.4	2.7	6.3	38	3.4
2	4.2	1.5	3 583	2.8	4.1	8.8	46	6.6
3	4.1	1.5	2 417	4.1	3.4	7.2	64	5.9
4	3.8	1.8	3 917	2.6	5.7	9.5	41	6.5
5	4.1	1.6	2 000	5.0	3.3	6.8	70	6.6
6	3.9	2.2	1 417	4.1	4.1	6.6	79	3.7
7	4.1	2.1	2 167	4.9	4.9	8.1	68	4.6
8	4.1	1.7	2 500	4.0	3.6	7.5	63	8.7
9	3.8	1.7	4 250	2.4	4.4	7.1	36	4.0
10	3.8	1.8	4 083	2.4	5.4	8.7	39	5.6

3.3 Effects of site parameters on tree growth

The geographical and soil parameters were analysed by PCA. Altogether, we analysed eight selected variables, which resulted in two significant axes. These new variables together accounted for 81.2% of the total variance (*Table 4*). PCA1 was positively correlated with pH, $CaCO_3$, OM, and PAW. The higher amount of OM represented more organic colloids that could retain more nutrients and water, which aligned with the growth of PAW. The negative correlation between the first axis and the proportion of sand had similar effects. More mineral colloids and less sand meant a higher proportion of silt and clay, which were accompanied by higher amounts of PAW. Therefore, water and nutrient availability characterised this axis. The second component (PCA2) was negatively correlated to the elevation and slope and positively correlated to PAP and sand fraction. This axis displayed an erosion gradient. The higher and/or steeper areas were more eroded, and the sand accumulated on the lower and flat areas along with the soluble phosphorus.

Table 4. Results of the principal component analysis (OM – organic matter, PAP – plant available phosphorus, and PAW – plant available water)

Axes:	PCA1	PCA2
Importance of components		
Eigenvalue	2.078	1.475
Explained variance	54.0%	27.2%
Cumulative proportion	54.0%	81.2%
Eigenvectors of environmental variables		
Elevation	-0.292	**-0.449**
Slope	-0.157	**-0.473**
pH(H_2O)	**0.436**	-0.127
$CaCO_3$	**0.404**	0.041
OM	**0.465**	-0.126
PAP	0.209	**0.580**
Sand fraction	-0.331	**0.366**
PAW	**0.409**	-0.264

Figure 3 illustrates the plain determined by the first two components and the scatter of the soil profiles. Soil profiles 1, 6, 7, and 9 grouped close to each other. All of these were Fluvic Cambisols. Profile 5 was in the same soil group; however, it separated from all the profiles. The rest of the profiles (2, 3, 4, 8, and 10) were Endocalcaric Luvisols and there was a larger distance between them than in the Fluvic Cambisols, excluding profile 5.

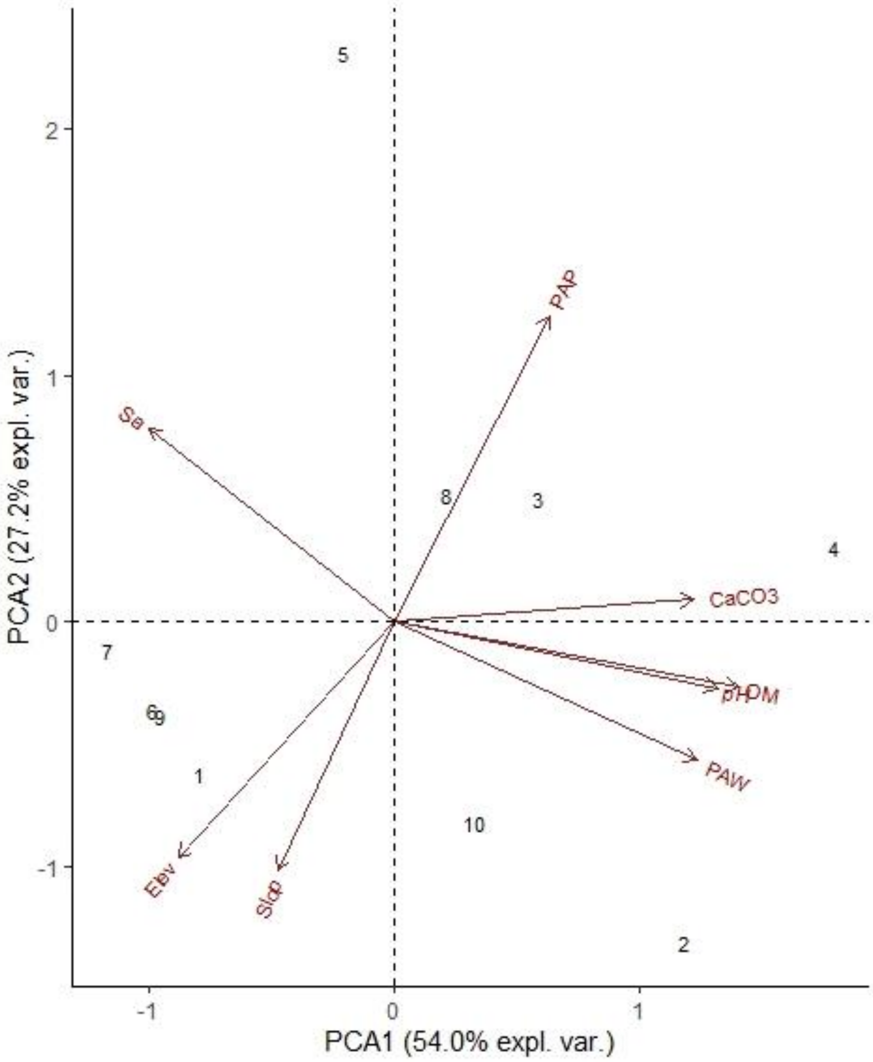

Figure 3. Ordination diagram of the PCA (Elev – elevation, Slope – slope, OM – organic matter, PAP – plant available phosphorus, Sa – sand fraction, and PAW – plant available water)

The stand parameters and the PCA axes were compared with correlation analysis. *Table 5* displays the results. PCA1 was strongly positively correlated with DBM, relative DBM, and RC. Other variables (S, RS) showed moderate negative correlations, while N and G had medium positive connections, and DBH had weak negative relations. Both H and relative H had weak positive correlations with PCA2. The DBM, relative DBM, and G showed weak negative relationships. Moderate negative connections were found in relative DBH and S, while RC showed a medium positive correlation. Strong relation appeared between PCA2 and N (-) and RS (+).

*Table 5. Correlation coefficients between PCA and stand parameters (H – mean height, DBH – mean diameter at breast height, N – number of trees, S – growing space, G – basal area, DBM – oven–dry aboveground biomass, RS – Reduction of the number of stems, and RC – resprouting capacity), significance level of the correlation is signed by asterisks (0 < *** ≤ 0.001 < ** ≤ 0.01 < * ≤ 0.05 < not significant)*

Variable	PCA1	PCA2
H (m)	0.17	0.28*
Relative H (–)	0.12	0.23*
DBH (cm)	-0.22*	-0.01
Relative DBH (–)	0.01	0.39*
DBM (Mg ha^{-1})	0.72**	-0.28*
Relative DBM (–)	0.82***	-0.23*
N (tree ha^{-1})	0.30*	-0.50*
S (m^2 $tree^{-1}$)	-0.40*	0.38*
G (m^2 ha^{-1})	0.33*	-0.28*
RS (%)	-0.30*	0.50*
RC (shoot $stump^{-1}$)	0.66**	0.39*

4 DISCUSSION

This study demonstrates the site characteristics and soil properties on marginal arable land affect the growth of hybrid poplars in SRC. Since the yield of an SRC is a key factor for the establishment of these plantations, the site factors must always be considered. Mostly marginal arable lands are used for woody biomass production in Europe, which is expected to produce – in practice – 2 to 10 Mg ha^{-1} yr^{-1} dry matter (Rae et al. 2009, Niemczyk et al. 2018). Several authors presented a much wider range of production rates (0–23 Mg ha^{-1} yr^{-1}) in poplar plantations from Europe (Rédei et al. 2009, Paris et al. 2011, Dillen et al. 2013, Röhle et al. 2015, Szabó et al. 2016, Kovács 2020) and these levels coincide with yields reported from North America (Shifflett et al. 2016). The economic threshold of the yields is highly dependent on the infrastructure of the countries. In Europe, 8 Mg ha^{-1} yr^{-1} is sufficient (Landgraf et al. 2020), while Posza – Borbély (2018) determined it as 12 Mg ha^{-1} yr^{-1} under Hungarian conditions. A poplar SRC network was established in Northern Italy along a soil quality gradient and its yields ranged between 5 and 15 Mg ha^{-1} yr^{-1} (with irrigation and fertilization). In comparison, our results – without fertilization and irrigation – show slightly betters yields than the poor-quality sites investigated by Paris et al. (2011), while Schlepphorst et al. (2017) had much higher yields (13–14 Mg ha^{-1} yr^{-1}) for 'AF2' on sites with no groundwater (i.e. groundwater level is deeper than 2 m from the soil surface). Di Matteo et al. (2015) reports 7 Mg ha^{-1} yr^{-1} average over Italy for poplar SRC, which is close to our results. Since our observation is based only on data from one growing season, it is a possibility that the average yield can reach an economically sound level over a 3–4 year rotation.

Higher yields in poplars can be achieved only where the site conditions are optimal for poplar cultivation, (i.e. groundwater is available as a surplus water resource for the trees, the soil is well aerated, and there is no lack of nutrients). Suboptimal areas produce lower yields, and the most important factors are nutrient levels, water, and the availability of these. Meteorological conditions also have a significant effect on the rates of biomass production (Ferré et al. 2021), especially where the groundwater is below the root zone and rain is the only water source for the plants (Heilig et al. 2021). The average FAI of the region is higher with more than one category range (1.27) than in the year of our survey (2020). The humid years provide better conditions for poplar SRC on sites where the groundwater level is not in the rooting zone. The former yields of the research plantation were 7–8 Mg ha^{-1} yr^{-1}. In 2020, similar average yields were observed, which is promising, especially if the severe spring drought – 11.1 mm under 51 days – is taken into consideration which happened in that year. This is because the older trees have more developed root systems which can compensate for drought.

The differences in growth show a close relationship with soil heterogeneity in the research area. The site conditions are suboptimal for poplar SRC, and this statement is validated by their relatively low yields compared to the economic threshold. The DBM production relates to the PCA1, which can be characterised as a nutrient and water availability gradient. This gradient indicates that the amount of biomass grown over the area is mostly determined by nutrient levels and their availability, and PAW in the soil. Better site parameters – higher values on PCA1 – provided more suitable conditions for hybrid poplars, along the higher values on this axis, there are higher DBM and lower RS. Since the RS was lower, the S is smaller, and the N is higher. Those areas where the soil is richer in fine particles and organic matter, with a more developed colloidal system, have higher nutrient levels and more stored water in the soil. This results in higher productivity of biomass above ground, which is in agreement with Bergante et al. (2010) and Schlepphorst et al. (2017); yields are determined by the water stored in the soil on marginal sites with no access to the groundwater (research questions I and II). However, Paris et al. (2011), found that clay percentage above 30% limits the growth of poplars. Nutrient levels are also important. PCA2 is represented as soil accumulation and erosion gradient. The lower areas are dominated by deposits richer in sand, while the higher and steeper areas have a clayey or loamy texture and a smaller amount of PAP. The gradient has a low correlation with most of the stand parameters. Height shows a positive connection. Salehei – Maleki (2012) reported a high correlation between height growth and clay fraction, PAP content of the soil, which is close to our findings. On a plantation with a groundwater table level close to the surface (<50 cm), Tufekcioglu et al. (2005) described a similar correlation in PAP, but they found that clay content has a negative correlation with mean height growth, which can be explained by the poor aeration of the soil. There is a moderate positive relation between PCA2 and RS, which explains the disadvantages of sandy soils. The higher proportions of macropores and the poorer colloidal systems – therefore the lack of both mineral and organic colloids – provide smaller pools of available nutrients and water, which makes these sites more sensitive to drought.

We set up clone specific equations to estimate biomass. However, Al Afas et al. (2008) found that most of the poplar clones can be described with one generalized model even over more rotations. Fortier et al. (2017) observed a similar trajectory of allometric equations over different sites and concluded that most of the poplar clones have a stronger genetic control than site effects on the relation between DBH and aboveground biomass. Further investigation of the models and a united dataset could give a more reliable model with broader usability, especially if former datasets – e.g. Vágvölgyi's (2014) – are incorporated.

The two clones show similar growth (research question III). Landgraf et al. (2020) reported similar results on 'AF2' and 'Kopecky' in the means of average biomass yield; however, the experienced RC was lower in their study, which can be explained by the higher RS and the enlarged growing space of the fourth rotation compared to the first and second. The two clones have similar traits and growth, which also supports the conclusions of Al Afas et al. (2008) and Fortier et al. (2017). In our findings 'AF2' has the higher average DBH and G, which is balanced by its lower timber density compared to the 'Kopecky'. These together resulted in insignificant differences between yields.

5 CONCLUSIONS

This study aimed to measure and explain the growth of a fourth rotation, heterogeneous SRC, planted with two poplar clones. To describe the soil diversity, we investigated soil pits and determined the most important physical and chemical parameters of the soil. This resulted in two different soil groups with different properties that can explain the difference in their growth. The most important soil characteristics proved to be the plant available water, soil reaction (pH), soil organic matter, and $CaCO_3$ content. To obtain more evidence, the soil characteristics were summarised in a nutrient and water availability gradient and an erosion–accumulation gradient. The nutrient–water availability is closely related to biomass yields which indicated that on a site with no access to the groundwater, the plant available water stored in the soil and the nutrient reservoir are dominant in determining the yields, while the erosion-accumulation gradient showed a weak correlation with most of the stand parameters. Our results demonstrate that the two clones, 'AF2' and 'Kopecky', show quite similar aboveground biomass production. Both clones react in the same way to marginal site and soil conditions. This multidisciplinary approach helps to describe the growth of an SRC established under suboptimal conditions, which can provide a basis for further studies and practice. Our results show that the site conditions are the key factors for the establishment and cultivation of SRC.

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