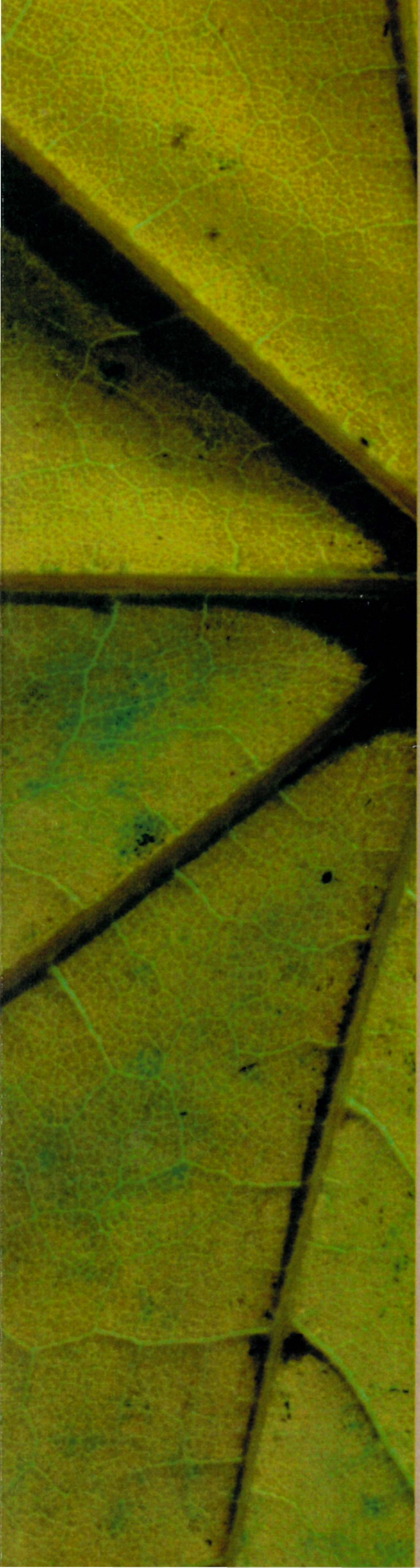

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Soil and Atmospheric Microclimate Research in Poplar Forestry Intercropping System in Hungary

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Abstract – Climate change presents growing environmental, economic, and social problems for the industrializing and developing world. Applying new technologies and transitioning to a cleaner, more flexible economy are essential to solving these problems. These solutions focus on climate change mitigation and work toward a complete transformation in line with sustainable development goals. Agroforestry systems are used for climate change adaptation and to support biodiversity. They also help combat desertification and soil erosion. Practical experiences show that applying forestry alley cropping systems can contribute to the climate adaptation of young forest stocks. The present study examined a historical forestry intercropping method known as *Vákáncsos* following the effects of microclimate stress on poplar seedlings (*Populus × euramericana cv. I-214*). This study investigated the background of previous observations concerning the practice of using intermediate crops in forest conditions – and the favorable results from these – and compared the stress effects on seedlings. When assessing the microclimate of the system, we used the EC tester (EC–electrical conductivity) to measure soil temperature and conductivity. We employed an agrometeorological hand-held instrument to measure air temperature, humidity, and wind speed. The results show that the agroforestry system significantly reduces temperature extremes and provides more favorable humidity. The agroforestry system reduced soil temperature values by 1–14 C° in the warmest period of the year. Experience and measurements indicate that the applied agroforestry practice can increase stress tolerance, afforestation efficiency, land use maximization, and profitability. Applied agroforestry can also serve other purposes like ecosystem services and feeding. Forestry alley cropping systems can be combined with resource efficiency.

Agroforestry / maize hybrid – P9241 / *Populus × euramericana cv. I-214* / soil conductivity / soil temperature

Kivonat – Talaj mikroklíma kutatás magyarországi erdei köztes termesztéses rendszerben. A klímaváltozás a mai iparosodó és fejlődő világunkban a környezet, a gazdaság és a társadalom szempontjából is egyre nagyobb problémát jelent. A probléma megoldásához olyan technológiák alkalmazására van szükség, amelyek lehetővé teszik az áttérést a tisztább, rugalmasabban alkalmazkodó gazdaságra. Ezek a megoldások nem kizárólag az éghajlatváltozás mérséklésére fókuszálnak, hanem a fenntartható fejlődés céljaival összhangban álló teljes átalakulást szolgálják. Az agroerdészeti rendszereket a világ számos táján sikeresen alkalmazzák a klímaváltozáshoz való adaptáció céljából, az elsivatagosodás, talajerózió ellen és a biológiai sokféleség támogatására. A gyakorlati tapasztalatok azt mutatják, hogy a köztes termesztés erdészeti alkalmazása segítheti a fiatal erdőállományok klímaadaptációját. Célunk az erdei körülmények között a közteskultúrát alkalmazó gyakorlat hatására kialakuló kedvezőbb mikroklímára vonatkozó korábbi megfigyelések hátterének tudományos igényű feltárása és a csemetéket ért stresszhatások összehasonlító vizsgálata. A rendszer mikroklíma-vizsgálataihoz a talajhőmérséklet és -vezetőképesség mérésére alkalmas EC tesztert, valamint a

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léghőmérséklet, páratartalom és a szélsebesség mérésére szolgáló agrometeorológiai kézi műszert használtunk. Az eredmények azt mutatják, hogy az agrár-erdészeti rendszer szignifikánsan csökkenti a hőmérsékleti szélsőségeket és kedvezőbb páratartalmat biztosít. A talajhőmérsékleti értékeket 1-14 C°-kal csökkentette az agrár-erdészeti rendszer. A tapasztalatok és a mérések alapján elmondható, hogy az alkalmazott agroerdészeti gyakorlat növelheti az erdősítés stressztűrését és ezzel a hatékonyságát, javítja a területkihasználást és a jövedelmezőséget, emellett pedig egyéb célokat is szolgál (ökoszisztéma szolgáltatások, takarmányozás). Az erdősítésben alkalmazott köztesnövény-termesztés így erőforrás-hatékonysággal és jobb gazdasági megtérüléssel párosulhat.

agroerdészet / kukorica hybrid – P9241 / *Populus* × *euramericana cv. I-214* / talajhőmérséklet / vezetőképesség

1 INTRODUCTION

1.1 Global presence of forestry alley cropping systems

Alley cropping is a plantation containing rows of trees and/or shrubs with agricultural or horticultural crops cultivated planted in between. Many parts of the world use alley cropping systems, but the number of systems that aim to increase the effectiveness of afforestation is limited. In these systems, alley cropping is used as one of the tools to mitigate the extremes of environmental impacts and compensate for human excesses (destruction of rainforests) by the local population.

Agroforestry systems created in this form in tropical-subtropical forest areas significantly improve the survival rate of tree individuals. In Africa, afforestation combined with intercropping aims primarily at food production and plays an essential role in soil improvement and erosion protection (Gichuru – Kang 1989, Kang et al. 1995, Watson 2014). The primary goal in South America and China is to replant and conserve forests, while agroforestry systems also provide food for local farmers and their families (Chamshama et al. 1994, Haggar et al. 2003, Fan A-nan et al. 2006, Suoza et al. 2010, Muwamba et al. 2015).

In Kenya and Sudan, the taungya management of agroforestry systems is established for successful industrial plantation and engages in the surrounding forest ecosystem. The shamba system is a well-known agroforestry system in Kenya (KFMP 1994). It includes ligneous vegetation combined with horticultural or agricultural intercrops managed by entrepreneurial mind farmers in forestland for 3–4 years. The area between the trees is made available for the farmers in exchange for free labor, which includes planting and caring for tree seedlings (Mburu 1981, Oduol 1987). After clearcutting, the farmers in taungya systems grow food crops (mainly corn, beans, potatoes, cabbage, and carrots) for one cropping period and then plant tree seedlings with intercrops for 3–4 years, followed by sole ligneous vegetation due to canopy closures (Wanyeki 1981).

1.2 Forestry alley cropping systems in Hungary

Forestry alley cropping has a long tradition in Hungary – especially in the eastern regions in the Great Plain – and was known as *Vákáncsos* historically. The Hungarian word *vákáncs* comes from the Latin word vacans. This word appeared on authentic instruments in Debrecen at around 1820. The name referred to abandoned and degraded forest areas. Hungary's state-owned forests were ruthlessly destroyed until the mid-1800s, which finally led to the need to compensate for the growing volume of deforestation in the eastern counties. Cost-effective reforestation was promoted as a solution. To moderate rising unemployment and accelerate afforestation at the same time, Debrecen's city management granted the designated afforestation areas to unemployed people possessing an entrepreneurial spirit (Miklós 1974). Hence, people living there took the name *Vákáncsos* from the area called "Vákáncs". They lived in the clearcutting areas and grew agricultural crops among the tree seedlings during their stay. After 3–5 years – depending on the tree species – they moved to another designated forest parcel (Balogh 1935). Though the Vákáncsos lifestyle is a thing of the past, the technology used has survived. Forestry professionals and forest land tenants in Hungary still employ the method, but the practice is not widespread. The overall aims include maximum area utilization, tree seedling protection, successful afforestation, and wild fodder provision. Although forestry alley cropping still exists in Europe, the technical sophistication of this method in some places has remained at the initial level.

1.3 The impact of climate change on domestic forests of Hungary

Climate change is a growing problem in our developing world, both naturally and socio-economically (Richard et al. 2000, Ramsfield et al. 2016, Isabel et al. 2019). Weather extremes, which are becoming more and more common both in Hungary and internationally, have a significant impact on the climate of a forest area which, being a production factor, has a strong influence on the forest ecosystem. From 1960 to about 1970, Hungary developed a forest climate classification system based on the forest aridity index (FAI) and Kaminszki's results (Führer 2018). The changes in aridity in recent decades have prompted the expansion of the classifications from four to five in number (Steppe), i.e. Hungarian forests now have five classes:

- Beech with *Fagus sylatica L.*
- Pannonic woods with *Quercus petraea (Matt.) Liebl.* and *Carpinus betulus L.*
- Pannonian-Balkanic turkey oak –sessile oak with *Quercus cerris* and *Quercus petraea (Matt.) Liebl.*
- Forest-steppe
- Steppe

Global warming has caused the emergence and territorial spread of the steppe climate class. Climate predictions for the 21st century show rising average temperatures and decreased rainfall in the main growing period of ligneous vegetation (May–August), being most critical in July–August in Hungary. These changes are projected to lead to a significant increase in the less profitable forest-steppe areas (up to 30%) by 2050 (Gálos – Führer, 2018). According to some estimates, the spread of the forest-steppe area will cause the beech climate in Hungary to disappear (Führer 2011). The issue is serious as it pertains to the tolerance of tree species (Szép 2010) and, thereby, the necessity of a shift in forest management. The inadequate conditions give rise to biotic pests that weaken resistance and, thus, reduce the assimilating surface and decrease the survival rate of trees. At the same time, the biomass yield of stands also decreases (Führer 2018), which is accompanied by a deterioration in wood quality (early-late wood) (Szép 2010).

Preventing this process is often only possible by using species that are better adapted to the changes expected in the long term. Practices that aid in climate adaptation can complement this measure. In non-protected forest areas, forestry alley cropping systems can be used as an effective tool for successful afforestation and to create the optimal conditions that support improved adaptation in vulnerable young stocks.

1.4 The benefits and disadvantages of forestry alley cropping systems

Depending on tree species, intercropping systems are used in the initial years of afforestation, before the crown gradually intensifies the competition between trees and intermediate plants. However, this also hinders the proper care of the tree stand. The cultivation of intercrop species is limited to 1–4 years, depending on the species. The length of intermediate cultivation can be increased by changing the crop species according to the growing intensity of the trees as needed, but this will not necessarily have the same positive effect on tree development in later years. Concerning crop yields, it is not worthwhile to apply this practice beyond a single growing season when associating a fast-growing tree species with a light-intensive intercrop because the stand canopy closes quickly, causing a drastic decline in the yield of the complementary crop. With slower-growing tree species – such as areas afforested with domestic oaks, where the row spacing is at least three meters – it is possible to apply a form of intermediate cultivation adapted to the given area for up to three growing seasons. Nineteenth-century documents attest that intermediate crops were used in the same field for up to five consecutive years (Miklós 1974). Research results in Hungary and other countries demonstrate that this form of agroforestry affects the microclimate of young forest stock. It helps tree seedlings survive during the initial, critical years, develops healthy and more resilient young forests, and, thus, supports the climate adaptation process in the forestry sector (Dalland et al. 1993, Quinkenstein et al. 2009, Nair 2013, Vityi et al. 2016, Vityi – Kovács 2018; Kovács et al. 2019, Xu et al. 2019).

One of the biggest disadvantages of the technology is the limited possibilities for mechanization, which can even deter entrepreneurial farmers from applying it. The selection of crop components is based on the forest site type of the forest area, the purpose of utilization, and the forest site characteristics. Even if these factors narrow the range of cultivable crops, the system to be developed will at the same time compensate for this by adapting to the climate. Temperate areas are in a more difficult position than warmer zones when it comes to choosing plant combinations because the environmental effects of warmer regions allow for a larger number of species and variety choices (e.g. non-frost sensitive species); therefore, agroforestry systems are much more diverse there. In the flat regions of Central Europe, the main tree species combined with agricultural crops are poplar (*Populus spp.*), black locust, (*Robinia pseudoacacia L.*) and in some cases oak (*Quercus spp.*) (Eichhorn et al. 2016, Paris – Dalla Valle 2017, Paris et al. 2018, Kay et al. 2019).

1.5 Purpose of the research

Intercropping is currently used for reforestation in the territories of several forestry enterprises in Hungary. The experience gained so far is related to the increase in the effectiveness of reforestation, the improvement of the health status and survival rate of the seedlings, and the observation of some other positive effects, which were explained by the presence of the crop. However, no research explaining such favorable experiences has been completed in Hungary to date, and only a few results related to the topic – focusing mostly on soil improvement aspects – can be found in the international literature. Therefore, the main goal of this research is to examine what environmental changes occur in a forest system combined with intercropping and which factors may play a role in these changes. The studies focused primarily on measuring changes in the microclimate of the system. The research examined the following hypotheses:

i) due to the higher vegetation cover, the agroforestry system (AF) reduces air temperature and soil temperature extremes compared to the control area of non-intercropped trees (CO);

ii) the intermediate crop increases the surface roughness, which significantly modifies the wind speed;

iii) the agroforestry system (AF) produces better soil moisture indices in the upper 10 cm of the soil and

iv) a more ideal humidity in the agroforestry system (AF) is likely due to the larger assimilating surface.

We have taken measurements in two locations in Hungary thus far – at Hajdúhadház (eastern Hungary, Great Hungarian Plain) and Kapuvár (western Hungary, Little Hungarian Plain). Preliminary experiments at Hajdúhadház Forest Management Unit served as the basis of the ongoing experiments at Kapuvár Forest Management Unit. This paper presents the portion of the research methods and results related to the microclimate studies completed at Kapuvár in 2020.

2 MATERIALS AND METHODS

2.1 Design of experimental area

Picture 1. Poplar alley cropping system at Kapuvár in 2020 (Klaudia Kovács)

The Kapuvári Forest Management Unit of Kisalföldi Erdőgazdaság Zrt. provided the possibilities for further field investigations planned by expanding the range of previously applied test methods. The new study area was established in 2020. *Table 1* shows the parameters for the AF and CO systems. Hybrid poplar long cuttings (2 m) with bare root (*Populus* × *euramericana cv. I-214*) were planted with a distance of two meters between stems and a row spacing of four meters. Maize was used as intercrop since it has been used for decades in poplar afforestation in Hungary. P9241 Optimum® AQUAmax® - FAO 340 maize hybrid was sown in four rows with a row spacing of 75 cm in the hybrid poplar plantation (*Picture 1*, *Figure 1*). This variety tolerates extreme weather effects and has a good yield and fast water release, ensuring quicker harvesting (keeping game damage prevention in mind). In order to achieve a good yield, the areas are selected each year to develop an agroforestry system that is unflooded at any time of the year.

Two adjacent areas were selected for the design of the mixed system and control system. The site characteristic similarities of the two plots were expected based on the comparison of the documents describing the forest subcompartment. However, the size of the area made soil sampling necessary, which may indicate possible inhomogeneity or any imparity in the soil. Sub-sampling points were selected in each plot along the diagonals where aggregate samples were made from the upper 15 cm layers of the soil. Each aggregate sample weighed 0.5 kg taken from a minimum of 20 sampling points. In addition, spot samples were taken at 3-3 points from a depth of 60 cm. In the laboratory test pH (H_2O) and pH (KCl), liquid limit (KA), total carbonate content ($CaCO_3$%), fine organic matter content (%), easily soluble phosphorus (P_2O_5 mg / 100 g) and potassium (K_2O mg / 100 g) were determined (90/2008. (VII. 18.) FVM regulation). Mechanical weed control was applied in both parcels in addition to the use of a brush cutter in the tree rows and two times harrowing in the control plot in early spring.

Table 1. The main features of the experimental area

Main features	Agroforestry	Control
Köppen-Geiger climate classification	Cfb	Cfb
Hydrology	Wet until surface	Wet until surface
Type of soil	Flat bog	Flat bog
Surface soil	Moderately deep	Moderately deep
Tree species	Hybrid poplar	Hybrid poplar
Coordinates	47°41’33.0”N, 17°02’06.0” E	47°41’32.4”N, 17°02’0.4.0”E
Forest subcomponent	Kapuvár 21 /C2	Kapuvár 21 /C2
Forestry region	Fertő-Hanság basin	Fertő-Hanság basin
Natura 2000	Not included	Not included
Owner	Hungarian State	Hungarian State
Primer function	Wood producer	Wood producer
Next forest management plan	2026	2026
Type of protection	No	No
Fire risk	Low	Low
Area	~1,0 ha	~1,0 ha
Cultivation	hybrid poplar, corn	hybrid poplar
Number of cutting	1320 pieces/hectare	1320 pieces/hectare
Sowing density	~80 000 seed/hectare	-
Distance of rows (cm)	~90 -75-75-75- ~90	400
Planting distance (cm)	200	200
Tree rows orientation	northwestern-southeastern	northwestern-southeastern
Gradient	plain	Plain
Irrigation	Drainage canal	Drainage canal
Game control	Wildlife fence	Wildlife fence
Plant protection	-	-
Period	1 year	1 year

[*] C- warm temperature, f-fully humid, b- warm summer

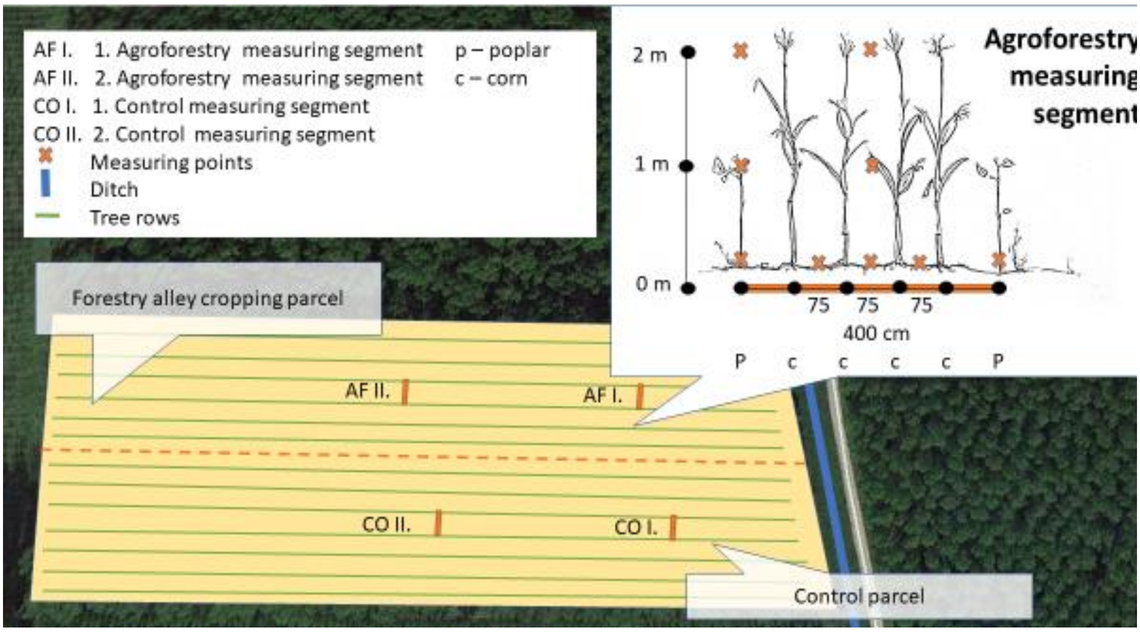

Figure 1. Experimental plot

2.2 Microclimate survey

Soil temperature, soil conductivity, air temperature (registered locally by the forest company), and air humidity (provided by the meteorological station at Andau, Austria, located within 15 km) were measured in July and August 2020. According to the results of domestic climate research, these two months are the most physiologically critical within the main growth period (May–August) (Bihari et al. 2018, Führer 2018). Table 3 lists the devices used for the measurements and the number of sampling points. We selected 2–2 measurement sections per plot (*Table 2.*) to model the cross-section (segments) of the areas. This is similar to the arrangement used in domestic and foreign experiments in shelterbelt and alley cropping systems (Danszky 1972, Singh et al. 1989). In this way, the study design included repetitions; however, the number of sections was limited as mobile instruments do not allow simultaneous measurements. To reduce the risk of measurement errors caused by rapid weather changes, the daily duration of the measurement should also be kept to a minimum. For this reason, the maximum measurement time interval was set at 2 hours. Measurements were made between 12 p.m. and 2 p.m., as the temperature is highest between 12 p.m. and 3 p.m. due to the strong radiation from the sun in this early afternoon period (Daut et al. 2012, Stefan – Iain 2016). Microclimatic parameters were measured every two days unless a major precipitation event prevented the measurements. These sorts of events affected 17% of the pre-planned measurement times.

Measurement of soil conductivity was made to compare the agroforestry (AF) and the control (CO) plots in terms of soil moisture. According to Hungarian and international research results, there is a close correlation between the electrical conductivity of the soil and the soil moisture content, provided that the site conditions are similar (*Figure 2*) (Bai et al. 2013, Milics et al. 2017).

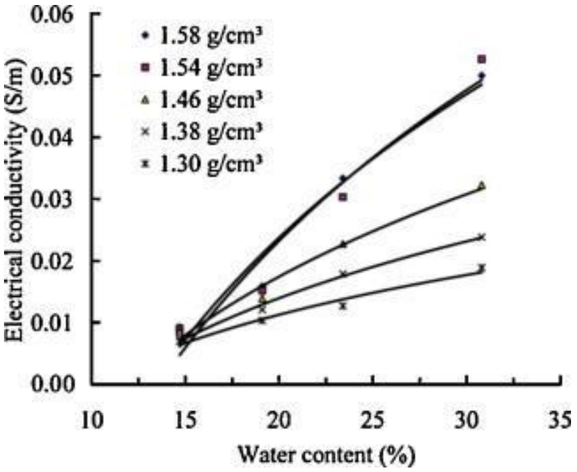

Figure 2. The relationship between electrical conductivity and water content of soil according to soil density (Bai et al. 2013)

Table 2. Features of examined parameters in 2020

Parameters	Soil temperature	Electrical conductivity	Air temperature	Air humidity
Period	Jul. 01-Aug. 30. (2020)	Jul. 01-Aug. 30. (2020)	Jul. 01-Aug. 30. (2020)	Jul. 01-Aug. 30. (2020)
Measuring	2 segments/parcel	2 segments/parcel	2 segments/parcel	2 segments/parcel
Plot	5 points/ segment	5 points/ segment	2 points/ segment	2 points/ segment

The 2-2 measurement sections were placed in the plots mirror-symmetrically to exclude the edge effect (*Figure 1*). In each measurement section, five sampling points were selected on an imaginary line perpendicular to the rows of trees connecting two poplar trees planted opposite each other, (2 points) and in the lane between the rows of trees (3 points) at equal distances from each other. Soil temperature and soil conductivity were measured at two depths (0 and 10 cm) per point. At the same sampling points, air temperature and humidity were also detected on the ground surface and, using a measuring rod, at heights of 1 m and 2 m. The wind speed was measured at 2 m and in the same orientation. The above parameters were performed with the instruments detailed in *Table 3*.

Table 3. Features of the devices used for the experiment in 2020

Name	Hanna HI 98331		KESTREL 3000		
Company	Hanna Instruments Inc.		Nielsen-Kellerman		
Country	US		US		
Parameter	Soil temperature	Soil conductivity	Air temperature	Wind speed	Relative humidity
Accuracy	0.1 °C	0.01 mS/cm	0.1 °C	0.1 m/s	0.1 % RH
Range	0.0 to 50.0 ºC	0.00 to 4.00 mS/cm	-29.0 to 70.0 °C	0.0 to 40.0 m/s	5 to 95% 25°C non-condensing

2.3 Data analysis

The microclimate data were analyzed by using main effects ANOVA after logarithmic transformation of those variables that violated the normality assumption. A one-way ANOVA was applied for the data of soil temperature, soil conductivity, and wind speed. A two-way

ANOVA was used for the data of air temperature and conductivity in each of the three studied layers (soil surface, 100 and 200 cm above soil surface). The main experimental factors are chosen Cultivation System (CS) (with AF and CO thesis) and Alley Position (AP) (with tree intra-row and tree inter-row). As a result, we get the impact of different parameters, including the interaction of the Cultivation System (CS) and Alley Position (AP). We used TIBCO Statistica ™ version 13 for statistical analysis. Statistical samples are the results of microclimate measurements of the same dependent variable on two independent groups (agroforestry and control area). The means of the obtained variable were compared. Statistical samples were taken from a normally distributed population, so the dependent (studied) variables were continuous. By statistical evaluation of the microclimate result, we can determine whether there is a significant relationship between the agroforestry plot and the control plot.

3 RESULTS

3.1 Soil test results

Despite being adjacent, flat areas are managed similarly. Contrary to the information included in the forest subcompartment description sheets, the soil test results show that the mixed stand and afforestation without crop have different site conditions showing a more favorable control area in terms of humus, phosphorus and potassium content but similar in terms of soil texture, pH and $CaCO_3$ content (*Table 4*), which may explain the changes in soil conductivity values.

Table 4. Soil characteristics of the experimental parcels

Item	Depth of layer (cm)	pH H_2O	pH KCl	$CaCO_3$ (%)	Hygro-scopy (hy%)	(KA %) ^{A}	humus (%) ^{B}	P_2O_5 ^{C} (mg/100g)	K_2O ^{D} (mg/100)
AF	30-60	8.0	7.8	32.1	1.1	48.5	0.7	0.8	14.9
CO	30-60	7.9	7.7	31.8	1.2	51.0	0.9	1.0	7.8
AF	0-30	7.5	7.2	16.4	3.6	63.8	7.2	4.0	20.5
CO	0-30	7.3	6.9	15.1	5.1	70.8	13.3	12.4	41.1

A: Upper limit of plasticity according to Arany, B: Fine organic matter content, C: Easily soluble P, D: Easily soluble K

3.2 Result of the microclimate test

3.2.1 Soil temperature

The soil temperature results confirmed the hypothesis based on previous observations and measurements; lower soil temperatures are expected in mixed crops due to cover (Mohammad et al. 2018) (*Figure 3*).

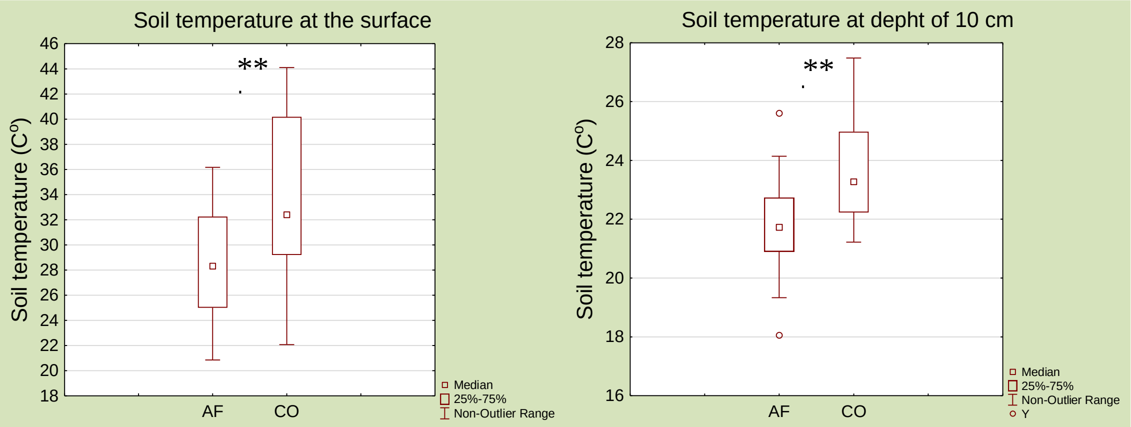

Figure 3. Soil temperature at the surface and depth of 10 cm in 2020 (AF - Average values from agroforestry measuring segment, CO - Average values from control measuring segment, n=200 observation, *significance level:***$p \leq 0.01$*)*

The soil temperature values of the agroforestry system are significantly lower compared to the control area, both at the soil surface and at a depth of 10 cm. The data also show that the soil temperature at a depth of 10 cm reflects sudden changes in air temperature with smaller fluctuations (F = 24.88, p ≤0.01; *Figure 3*). Soil surface temperature data for the agroforestry area provided more favorable values (F = 14.94, p ≤ 0.01; Fig. 3) even when compared to values measured at a depth of 10 cm in the control area. The difference between the two examined soil depths was on average 8 °C in the case of the mixed system and 10 °C in the control area. If the comparison is made for the same soil depths and by comparing the two different systems, a difference of 1–14 °C in the soil surface temperature and 5 °C in the 10 cm depth can be found.

3.2.2 Electrical conductivity (EC)

Figure 4 shows that the control system produced higher values by 0.1 mS/cm on average. During data evaluation, a significant difference was observed between AF and CO systems (F = 11.61, p ≤0.01; *Figure 4*). In the case of the same site conditions, this would suggest that the control area has more favorable soil moisture conditions. However, the different soil properties of the two plots make the interpretation of the obtained values practically impossible due to the many interrelated factors.

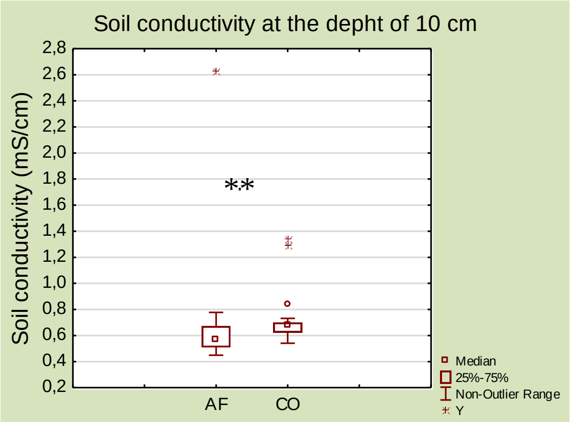

*Figure 4. Electrical conductivity at a depth of 10 cm in 2020 (AF - Average values from agroforestry are measuring segment, CO - Average values from control measuring segment, n=200, significance level:***$p<0.01$*)*

3.2.3 Air temperature and humidity

We observed that the mean atmospheric temperature differences decreased for the two plots as we moved away from the soil surface, but a non-significant difference between the values of the two areas was observed. Regarding humidity, higher values were detected in the AF system, but these were non-significant, even in the case of pairwise comparison of the tree rows and of raw spacings of the different treatments (AF vs. CO). The results of the wind speed measurement showed that the crop vegetation reduced the turbulent exchange of air even at the height of 2 m (*Figure 5*). As air movement decreases, higher humidity develops under the canopy, so the vegetation evaporates less intensively, which improves the water management of the system.

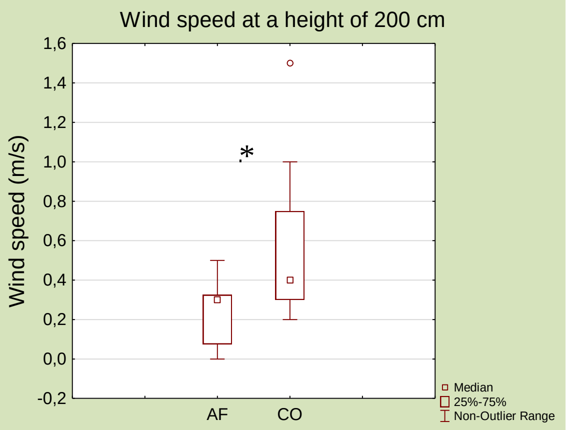

*Figure 5. Wind speed in 2020 (AF – Agroforestry system values, CO – Control system values, n=80, significance level: *p<0.05)*

The distribution of visually observed crop cover is also in line with the above results, which influences the degree of moisture retention, i.e. the higher degree of cover (AF I.) resulted in higher humidity than in the plot with lower plant density (AF II.). Higher vegetation density and the associated higher humidity reduce the local impact of atmospheric drought where, due to the high temperature and low humidity, the potential evaporation increases to such an extent that the vegetation is unable to increase evaporation adequately even if sufficient water is available in the soil. Two-way ANOVA analysis (*Table 5*), cultivation system (CS), alley position (AP), and their interactions (CS x AP) as fixed effects showed that the impact of different treatments on air temperatures was not significant, and the effects on air humidity were similar than on the values of the air temperature (*Figure 6*).

Table 5. Results of two-way ANOVA analysis for the effects of Cultivation Systems (CS) and Alley Position (AP) on the measured parameter

Air temperature	CS		AP		CS x AP	
	F	p	F	p	F	p
surface	1.547^{ns}	0.217	0.065^{ns}	0.799	0.770^{ns}	0.383
1.00 m	1.126^{ns}	0.292	0.000^{ns}	0.989	0.216^{ns}	0.643
2.00 m	0.541^{ns}	0.464	0.002^{ns}	0.965	0.247^{ns}	0.621

Air humidity	CS		AP		CS x AP	
	F	p	F	p	F	p
surface	0.041^{ns}	0.839	2.835^{ns}	0.096	0.585^{ns}	0.447
1.00 m	0.006^{ns}	0.940	1.554^{ns}	0.216	0.416^{ns}	0.521
2.00 m	0.006^{ns}	0.940	1.112^{ns}	0.295	0.019^{ns}	0.892

ns: non-significant

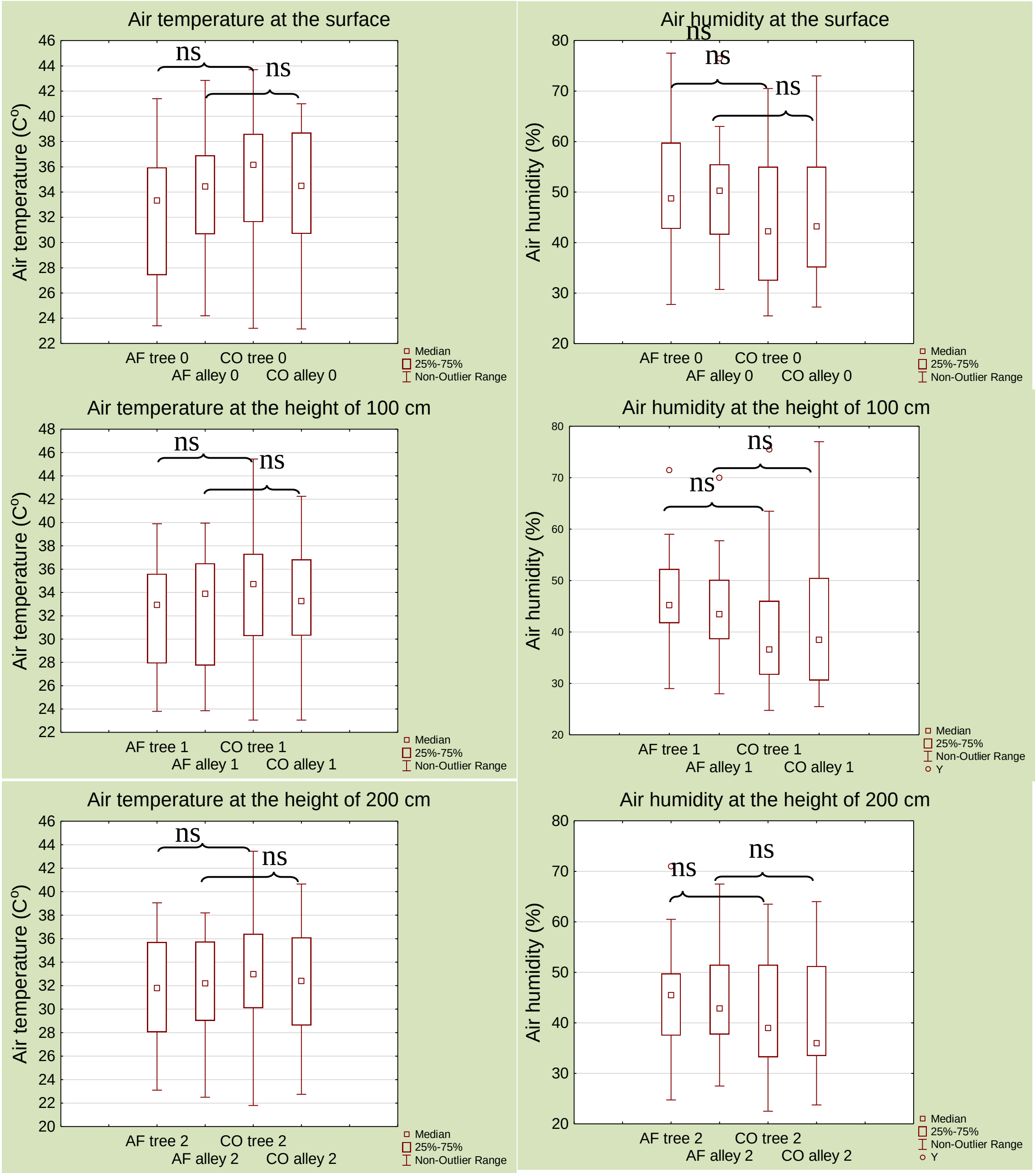

Figure 6. Air temperature and humidity values in 2020 (AF alley - Agroforestry segment values from alley, AF tree - Agroforestry segment values from tree row, CO alley - Control segment values from alley, CO tree - Control segment values from tree row, n=40, significance level: ns: non-significant)

4 DISCUSSION

Agroforestry management is more complex than the management of afforestation or homogeneous agricultural crops due to the deliberate association of several plant species. As the complexity increases, the system of processes and effects also becomes more complicated, making it more challenging to isolate the factors that influence the values measured during field studies. Therefore, this study was designed to keep the degrees of freedom to the minimum as far as possible to ensure similar soil management and water supply, use of the same tree species and tree planting structure, and chemical-free cultivation in both the intercropped and the control area.

The AF system showed statistical significance at $p \leq 0.05$ in terms of the soil temperature at the surface and 10 cm below the surface compared to the control plot. Furthermore, differences have been found in terms of air temperature and humidity between for the benefit of the intercropped area. The more favorable air temperature values of the agroforestry system have a remarkable effect on plant development because they act as a catalyst for many biological processes, influencing soil moisture content, aeration, and plant nutrient availability (Müller et al. 2016, Onwuka – Mang 2018). Even a few degrees of variation can significantly modify biomass yields (Luo et al. 2020), or the germination rate may be reduced due to high soil temperatures (Huang et al. 2008). Consequently, even a small change can have a serious impact on the development of the forest stock because extremely high temperatures can affect agricultural crops and woody vegetation (Petzold et al. 2011).

In addition, a significant difference was found in terms of soil and plant water regimes. The authors observed that even at the height of 2 m, the crop between the tree rows contributed to wind speed reduction, which makes it likely that water utilization was more efficient in this part of the area. Although rainfall interception is higher in the AF system due to the higher vegetation density, the vegetation absorbs the precipitation from heavy rain better; therefore, the rate of infiltration into the soil is also better. The importance of this function may grow in the future due to the expected increase in extreme precipitation events due to climate change (Semmler – Jacob 2004). These positive effects improve the water balance, reduce the probability of atmospheric drought, and improve system performance. The differences in the experimental area – discovered in parallel with the microclimate studies – cause uncertainties in the evaluation of the results of the conductivity measurements and, thus, in the determination of the effect of the land use practice on the soil moisture content; therefore it is not possible to draw sufficiently substantiated conclusions in this respect. Thus, the authors aim to perform further, additional studies in the future for the comparative study of soil moisture.

5 CONCLUSIONS

In summary, we conclude that soil temperature and wind speed showed significantly favorable values in the intercropped forest plantation compared to sole tree vegetation. To analyze the impact of the intercropping systems on the water management of the forest stock, we plan further studies and supplement the range of the studied parameters and test methods.

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Climate Change Induced Tree Mortality in a Relict Scots Pine (*Pinus sylvestris* L.) Forest

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Abstract – Mortality appeared in a relict Scots pine (*Pinus sylvestris* L.) forest where the sandy pine forest association (*Pinetum-Festuco vaginatae sylvestris*) is unique in the Carpathian Basin. To identify the complex causes of tree mortality, we analysed the climatic and soil conditions completed with bryological and biotical (pests) surveys. Altogether the results show that unfavourable soil conditions (coarse sand) and increasing aridity have led to a decline in tree vitality. Bark beetles have a high population density in the stand, and they have colonised both the felled trap trees and the standing trees, where the beetles contributed to tree mortality. New spreading invasive moss species have appeared in the recently formed gaps, where crone projection is low. The disappearance of this relict forest stresses the urgent need for Hungarian forest management to prepare strategies for adaptive tree species selection.

climate extremes / damage chain / climate adaptation / relict forest association / water holdig capacity

Kivonat – Klímaváltozás okozta fapusztulás egy reliktum erdeifenyves (*Pinus sylvestris* L.) erdőben. A mortalitás jeleit tapasztaltuk egy reliktum erdeifenyvesben (*Pinus sylvestris* L.), mely társulás (*Pinetum-Festuco vaginatae sylvestris*) egyedülálló a Kárpát-medencében. A fapusztulás összetett okainak feltárása érdekében az éghajlati és talajviszonyokat elemeztük, kiegészítve briológiai és biotikus (kártevő) felmérésekkel. Az eredmények azt mutatták, hogy a kedvezőtlen talajviszonyok (durva homok) és a gyakoribbá váló aszályperiódusok vezettek az erdőállomány legyengüléséhez, majd pusztulásához. A szúbogarak populációsűrűsége nagy volt az állományban, és nem csak a kivágott fogófákat, hanem az álló fákat is megtámadták hozzájárulva ezzel pusztulásukhoz. Új, terjedő invazív mohafajok is megjelentek a felnyíló állományban ott, ahol alacsony volt a záródás. A reliktum erdő eltűnése még sürgetőbbé teszi, hogy a hazai erdőgazdálkodás mielőbb klímaadaptációs stratégiai lépéseket tegyen.

éghajlati szélsőségek / kárlánc / klímaváltozáshoz való alkalmazkodás / reliktum erdőtársulás / talaj víztartóképesség

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1 INTRODUCTION

Threats to the vitality of forest ecosystems depend more on the frequency and expected tendency of extremely hot and dry events than on the changes in the climatic means (Mátyás 2009). Recurrent and increasingly severe droughts have been observed in southern Europe in recent decades, while northern Europe has experienced an opposite tendency (Spinoni et al. 2005, Gudmundson et al. 2016). Forest ecosystems have already responded to prolonged droughts and heat stress with defoliation, crown dieback, reduced growth and production, and widespread mortality (Bréda et al. 2006, Allen et al. 2010, Lindner et al. 2014). Projected climate conditions (Jacob et al. 2014, IPCC 2021) pose an increasing risk to the forests (Allen et al. 2010). Mortality can occur rapidly under hotter droughts, associated biotic damages, and other disturbances (Hlásny et al. 2014, Allen et al. 2015). The Carpathian Basin is considered highly sensitive and vulnerable to climate change and the increased probability and severity of extreme events (Spinoni et al. 2013, Gálos et al. 2015). The xeric limit of Scots pine is located mainly at the foot of the Alps (Marqués et al. 2018). To the south-east and south-west of the latitude of the Alps, the xeric limit tends to occur only in patches in the high-mountainous landscapes at an altitude of 1000–2000 meters in southern Europe. From the Iberian Peninsula, studies have already reported that climate change has influenced forest stand structure and increased the competition between species in the case of Scots pine (Primicia et al. 2016, Marqués et al. 2018). The area already experiences drought-induced mortality (Camarero et al. 2015) and competition-induced mortality (Ruiz-Benitoet al. 2013). Moreover, negative impacts are observed in drier areas (Marqués et al. 2021, González de Andrés et al. 2018). The xeric conditions in Central Europe suggest the remaining stands of the middle mountains will disappear within two decades.

Vitality decline induced by abiotic damages leading to tree mortality is a serious problem in Hungarian forests (Berki et al. 2009). The large amount of these damages in recent decades suggests severe difficulties for forest management in the future (Mátyás et al. 2018). Forest sites with detectable drought-induced damages are increasing in Hungary (e.g. Rasztovits et al. 2013, Móricz et al. 2018). The investigated old-growth Scots pine (*Pinus sylvestris* L.) forest is located in a protected area. Climate, soil, and local hydrological conditions highly influence the health conditions of this relict forest stand. However, complex analyses assessing the observed tendency of all of these site factors are still missing. Examining each factor separately could encompass wide spatial and temporal scales. Nevertheless, the lack of information on other factors potentially creates biased assessments of conclusions about the inducing causes. Site conditions always affect vegetation. Conversely, vegetation always affects site conditions. Therefore, the relationship between forest stand vitality and stand growth becomes more complicated in the case of damage chain appearance in an elder, resistant forest stand. Our research aimed to answer the following questions:

1. How have site conditions and especially climate changed in the research area in recent decades?
2. Which key factors and mechanisms determine tree mortality in this pre-boreal forest?
3. Which are the most important site-limiting factors in this case?
4. What kind of biotic damage chain do the changing climate conditions induce?
5. Can a relict and protected ecosystem adapt to the changed conditions?

2 MATERIALS AND METHODS

2.1 Study area

The research site is located in the Transdanubian region. The area of the protected relict forest (called Fenyőfő) is approximately 578 ha, of which the investigated area is ca. 200 ha. *Figure 1* shows the sampling plots at the research site.

The age of the original community can be estimated at ~10 000 years (established 8000-7000 B.C.). Settlers who came to the area completed the community with special Scots pine seedlings in the middle of the 18th century (Babos et al.1966). Therefore, the vegetation types in the study area are *Festuco vaginatae–Pinetum sylvestris, Festuco rupicolae – Pinetum sylvestris*, and *Quercetum petraeae – Cerris pannonicum*, while the vegetation near creeks is classified as *Aegopodio – Alnetum* (Dövényi 2010). Majer confirmed the relict origin (a remnant of a formerly widespread species in an isolated area) of the forest at the end of the 19th century (Majer 1988).

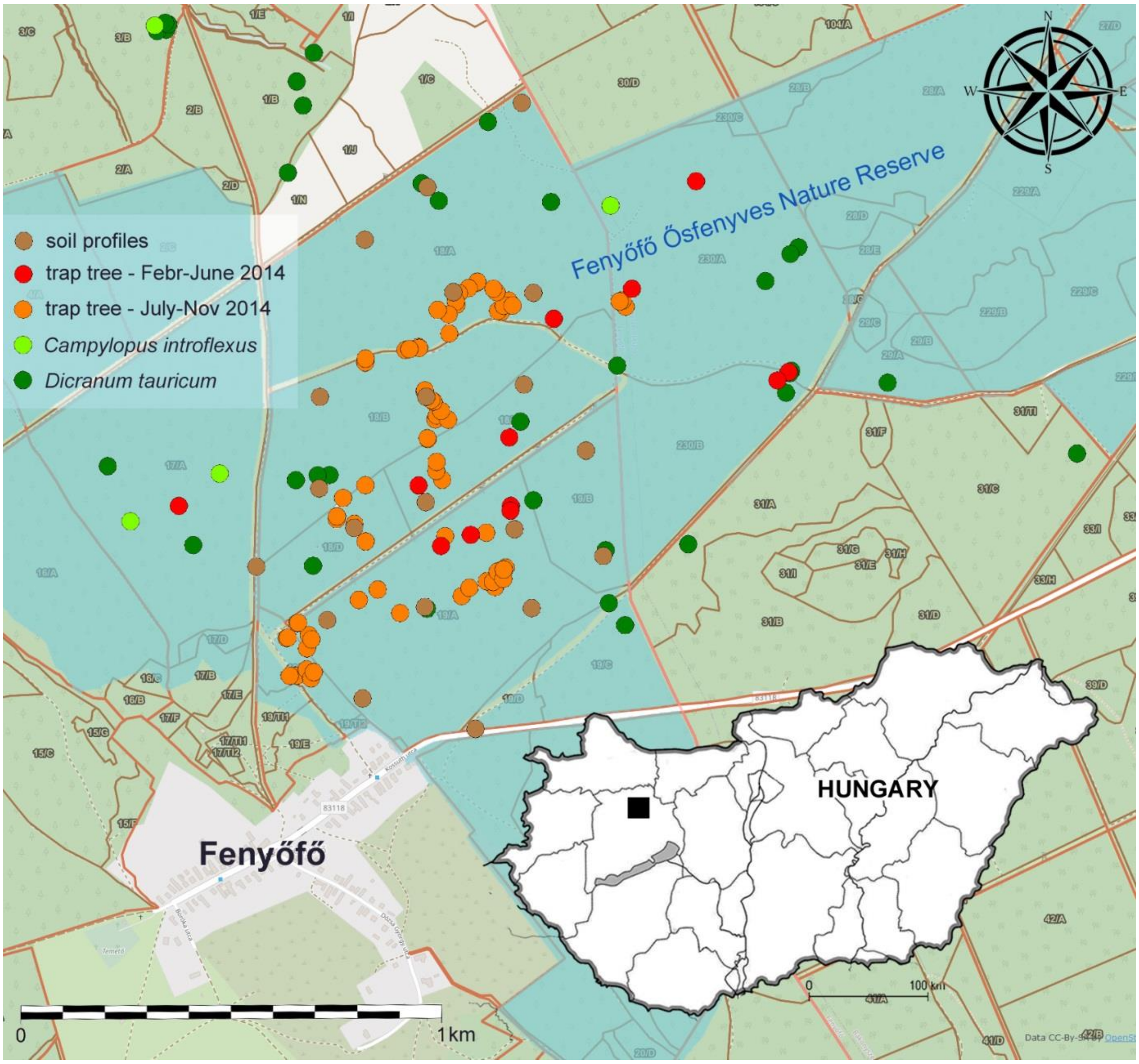

Figure 1. The location of the research site and the sampling points. (Numbers are showing the forest subcompartments)

The water streams of the area are periodic. The groundwater level is between 4–6 m, and is likely inaccessible to vegetation (Dövényi 2010); therefore, precipitation is the only water uptake option for vegetation. The precipitation sum in the vegetation period is 380 mm, which indicates a sufficient water supply in the area. The fluctuation of annual temperature is 21.8°C, which provides balanced climate conditions. Annual sunlight duration is above 1,980 hours; thus, the actual evaporation is high (Halász 2006). Soil texture shows that 56% of soils are sand, and 42% are loam. Soil texture and hydrological factors allow for versatile soil types in the area. We rarely detected perigon sand caused by sedimentation, while along streams, we found meadow soils (Babos et al. 1966). Climate and forest vegetation have leached out the carbonated quicksand, which led to the formation of humic sands, slightly acidic rusty brown, and lessivated brown forest soils.

Based on previous investigations, the Scots pine has existed since the dry and cold pine-birch age (Babos et al. 1966). The deciduous tree species could not displace the Scots pine from the sandy mounds, even during favourable climatic periods. The Scots pine mixed with different oak (*Quercus* spp.) and other deciduous tree species. Forests began to disappear due to land-use changes in the area in recent decades. Only a few individual trees survived this period; the saplings were used for a tree-planting program on sandy sites (Borhidi 2006). Scots pine forests (*Festuco vaginatae-Pinetum sylvestris*) are currently located on sandy mounds (Bartha 1995) and produce low crown closure stands. At the lower canopy level, Turkey oak (*Quercus cerris*), sessile oak (*Quercus robur*), and flowering ash (*Fraxinus ornus*) are present; Juniper (*Juniperus communis*) also occurs in the gaps. The mortality of Scots pine causes shrub species to gain ground, while the number of deciduous tree species is also increasing.

2.2 Methodology

The climate analyses are based on the nearest weather station datasets of the Hungarian Meteorological Service (OMSZ). There is no OMSZ station in the area of Fenyőfő; therefore, the data of Tés (47.26°É 18.03°K; 460 m a.s.l., 19 km distance from the study area) and Bakonybél (47.26°É 17.73°K; 286 m a.s.l., 10 km distance from study area) station were interpolated. Furthermore, the interpolated data were compared and corrected with local forestry measurements. Monthly temperature and precipitation time series, the total number of summer days (Tmax ≥ 25 °C), and hot days (Tmax ≥ 30 °C) per year were investigated for the period 1961–2021 (*Table 1*). Two climate parameters were calculated. PET (potential evapotranspiration (mm/month)) was determined based on Thorntwaite's formula (1948) (1).

$$PET = 16 \times \left(\frac{\mathrm{L}}{12}\right) \times \left(\frac{N}{30}\right) \times \left(\frac{10Td}{I}\right)^{\alpha} \qquad (1)$$

Where:

L: the average day length (hours) of the month being calculated

N: the number of days in the month being calculated

Td: the average daily temperature of the month being calculated

α: $(6.75 \text{ x } 10^{-7})\ \mathrm{I}^3 - (7.71 \text{ x } 10^{-5})\ \mathrm{I}^2 + (1.792 \text{ x } 10^{-2})\ \mathrm{I} + 0.49239$

I: $\sum_{i=1}^{12} \left(\frac{\mathrm{Tmean}}{5}\right)^{1.514}$

Aridity index was determined as the quotient of precipitation (P) and potential evapotranspiration (PET). We used a modified Thornthwaite-type monthly water-balance model (Thornthwaite – Mather 1955) based on mean monthly temperature and precipitation, soil texture, rooting depth, and the maximum amount of available water in the soil. We assumed water stress when the relative extractable water (REW) decreases below 40%

(Granier et al. 1999). In addition, the REW calculated by monthly temperature and precipitation data, soil physical diversity, root depth, available water volume (EW), and maximum water uptake (EWm) (2). Monthly precipitation was reduced by an interception to determine the annual drought stress index (Is) (3). With SWD, the water deficit stored in the soil could be calculated (4).

$$REW = EW / EWm \tag{2}$$

$$Is = \sum SWD / EWm \tag{3}$$

$$SWD = EWm * 0.4 - EW \tag{4}$$

Where:

REW: the relative extractable water content
EW: the available water volume
EWm: the maximum of water absorption
Is: the annual drought stress index
SWD: the water deficit stored in the soil.

We collected 119 samples from 20 soil profiles and identified the following soil properties:

- soil pH (potentiometrically in water and KCl suspension),
- texture (particle size distribution based on the Hungarian Standard (MSZ-08-0206)),
- $CaCO_3$ (Scheibler-type calcimeter),
- soil organic matter content (FAO 1990),
- ammonium lactate/acetic acid extractable (AL) potassium and phosphorus content (MSZ 20135:1999).

We evaluated the soil samples according to Van Reeuwijk (Van Reeuwijk 2002), and Stefanovits and colleagues (Stefanovits et al. 1999). We used C2 software to represent the data of selected soil profiles (Juggins 2007). Based on Stojanovic (Stojanović et al. 2015), we investigated the climatic response through tree ring widths as follows:

- 12 Scots pine trees with different health conditions were felled,
- two discs were taken from each pine tree:
    - one at breast height (1.3 m) (Group I),
    - one from root welling (0.1 m) (Group II),
- dry samples were sanded with progressively finer sandpaper until they acquired a highly polished surface (Stoke – Smiley 1968),
- after preparing the discs, we elaborated high-resolution pictures and measured the tree ring widths (TRW).

Several studies have described the bryophyte flora of the study area. Purger (Purger 1992) studied the bryophyte flora about 30 years ago, while a second bryofloristical study was performed in the spring of 2014 (Szűcs 2014, Szűcs – Patocskai 2014). In these two papers, the authors compared the main elements that influence changes in the bryophyte flora. During the field collections, the typical habitat and substrate, the time of collection, as well as the GPS coordinates and the altitude of the site points were recorded. The nomenclature of mosses and liverworts follows the classification of Hodgetts et al. (2020).

This study uses a broad spectrum of various methods to focus on a complex examination of the temporal change of the limiting site factors. Through an initial “rough” estimation of the new ongoing tendencies, we could detect the impact of dry years by applying relatively simple empirical methods (e.g., the tendency of narrowing *TRW*). More precise but expensive procedures are not required to fulfil the aim of our study. More accurate measurements are planned later to obtain more detailed information about specific drought events and their impacts.

Table 1. Analysed climate variables and indices

Selected climate parameters	Abbreviations	Time period
Mean air temperature	T	monthly, seasonal, annual
Maximum air temperature	T_{max}	monthly, seasonal, annual
Minimum air temperature	T_{min}	monthly, seasonal, annual
Precipitation sum	P	monthly, seasonal, annual
Summer days	$T_{max} \geq 25°C$	daily
Hot days	$T_{max} \geq 30°C$	daily
Extremely hot days	$T_{max} \geq 35°C$	daily
Ice days	$T_{max} < 0°C$	daily
Frost days	$T_{min} < 0°C$	daily
Cold days	$T_{min} < -10°C$	daily
Potential evapotranspiration	PET	monthly, annual
Aridity index	P/PET	monthly, annual
Dry days	DD; $P_{day} < 0.1$	daily

Pearson's correlation tests were used for the two groups of ring widths and temperature, potential evapotranspiration (*PET*), and aridity index (*P/PET*) as climate variables. The tree ring widths (TRW) were measured with AutoCAD 2015 software (released by Autodesk). For statistical analyses, SPSS vers. 20.0 and R 3.2.2 programs (IBM Corp. 2011, R Core Team 2018) were used.

3 RESULTS

Temperatures have exhibited a significant increase in the investigated region in the last 60 years, with the most intense increases occurring in summer. The temperature means and temperature extremes both indicate a robust warming tendency. The total number of summer days and hot days per year have been higher in 1991–2020 than in 1961–1990. In the early 1990s, 2000s, 2010s, and consecutive periods were extremely dry compared to the long-term mean (*Figure 2*). In these 3 to 4 long periods, low summer precipitation occurred together with high temperatures that enhanced the severity of the drought condition.

We used both extreme low and high high-temperature indices in our investigation. The average total number of cold days from 1961 to 1990 is 9 days/year and decreases to 7 days/year from 1981 to 2010. Similarly, the number of ice days declined (from 21 days/year to 20 days/year), and frost days also fell (from 89 days/year to 85 days/year). The total number of extremely hot days was 0 days/year during the 1961-1990 period and 1 day/year between 1981 and 2010. The total number of hot days increased from 12 days/year to 19 days/year; summer days increased from 63 days/year to 75 days/year (*Figure 3* and *Table 2*).

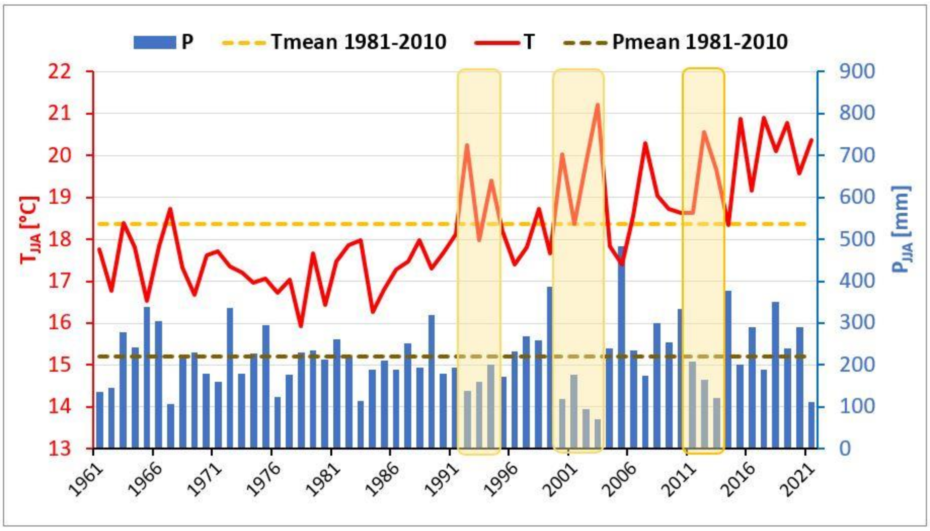

Figure 2. Mean summer temperature and precipitation sum for the period 1961–2021. Shaded areas indicate the consecutive drought periods.

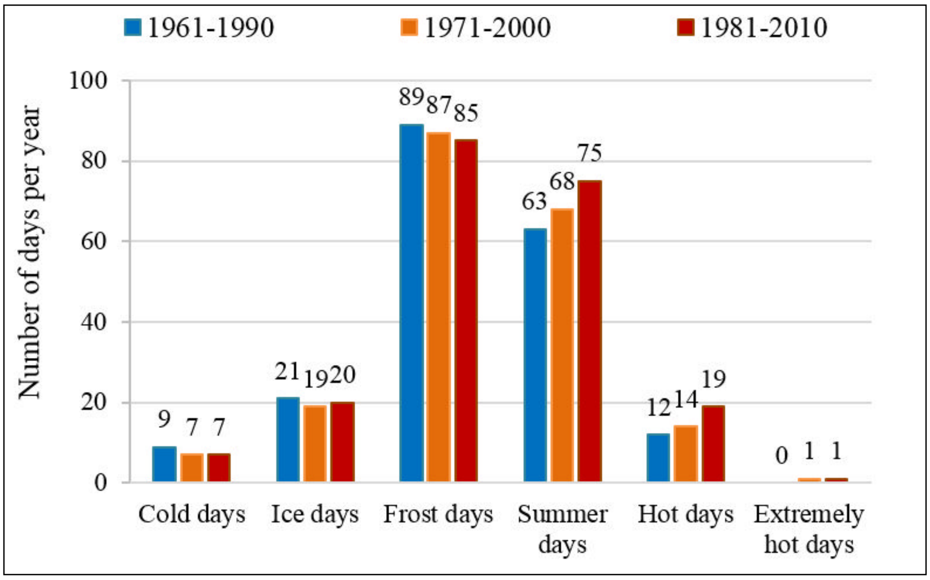

Figure 3. Total number of extreme low and high temperature in three different time periods (1961–1990; 1971–2000; 1981–2010)

Table 2. Differences between 1961–1990, 1971–2000 and 1981–2010 for temperature means (T) and dry days (DD). dT (°C) means the temperature differences and dDD (%) mean the dry day differences between 1981–2010 and 1961–1990 time periods. The bold red values are significant changes.

T (°C)	I.	II.	III.	IV.	V.	VI.	VII.	VIII	IX.	X.	XI.	XII.
1961–1990	-	0.9	5.3	10.2	14.8	18.0	19.7	19.4	16.0	10.6	5.5	0.4
1971–2000	-	1.2	5.8	10.2	15.1	18.2	20.1	20.0	16.0	10.6	5.2	0.9
1981–2010	-	1.1	5.8	10.9	15.7	18.7	20.8	20.5	16.2	11.0	5.8	0.7
dT (°C)	1	0.2	0.5	0.7	0.9	0.7	1.1	1.1	0.2	0.4	0.3	0.3
DD (days)	**I.**	**II.**	**III.**	**IV.**	**V.**	**VI.**	**VII.**	**VIII**	**IX.**	**X.**	**XI.**	**XII.**
1961–1990	1	13	15	15	14	13	17	17	19	19	13	13
1971–2000	1	14	15	15	15	14	16	18	18	19	13	13
1981–2010	1	15	16	16	16	16	18	18	18	20	13	13
dDD (pcs)	0	2	1	1	2	3	1	1	-1	1	0	0

The recurring hot and dry periods caused decreasing relative extractable water in the soil for *Pinus*. *Figure 4* shows that relative water capacity was below the water stress limit several times and decreased during the period 1990-2021. Water balance diagrams were prepared using the properties of the soils (e.g. texture, humus content), root depth, and the climatic conditions of the area. It is important to note that below a certain limit, plants cannot absorb enough water, and water stress develops.

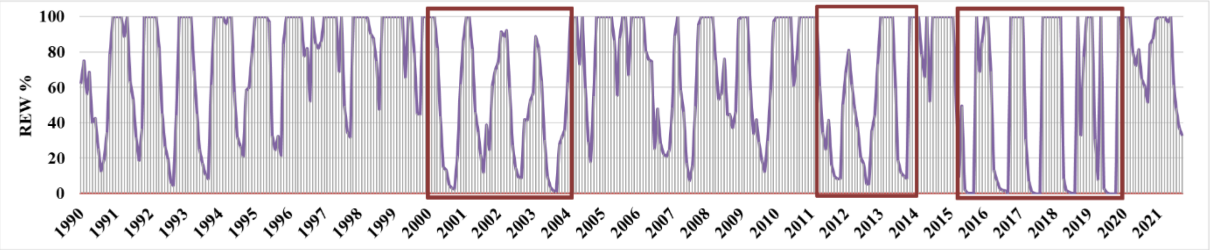

Figure 4. Relative water capacity based on Thornthwaite water balance model 1961–2021 (red frames highlighted the drought periods)

Soil types are very similar over the entire area. Soil pH (pH_{H_2O}) was between 4.2 and 8.5. Soil pH in the upper layers varies from the most acidic to the weakly alkaline categories (*Figure 6*), but most of the soil samples were acidic. The soil pH of lower layers was frequently alkaline. Leaching is characteristic in the soil profiles; this seems to be the leading cause of the acidic values in the upper layers. The results of (pH_{KCl}) were followed by the values of (pH_{H_2O}). Soil pH (pH_{KCl}) was between 3.5 and 8.3.

The $CaCO_3$ content of the soils was between 2% and 19% below 20 cm of depth, which is unfavourable to all of the present tree species. We also found very little saline (<0.5%) in the lower layers during the conductometric analysis. The sum of clay% (< 0.002 mm) and silt% (0.05-0.002 mm) fractions was low (between 3%–11% in the samples; thus, we classified them as coarse sand. Due to the low ratio of sedimentable soil particles, the water holding capacity of the investigated soils is unfavourable for the vegetation. The humus contents of the soils were between 0.01% and 8.8%. High values were found close to the surface, but they also occurred in lower layers (>40 cm depth), where buried humus layers were found in a few cases. The total nitrogen supply was between 0.01% and 0.25% of nitrogen; however, these levels are considered to be low rather than medium. AL extractable phosphorus content was low (3.4–15.9 P_2O_5 mg/100g soil), and AL extractable potassium ranged between 1.5–9.1 K_2O mg/100g soil (*Figure 5*).

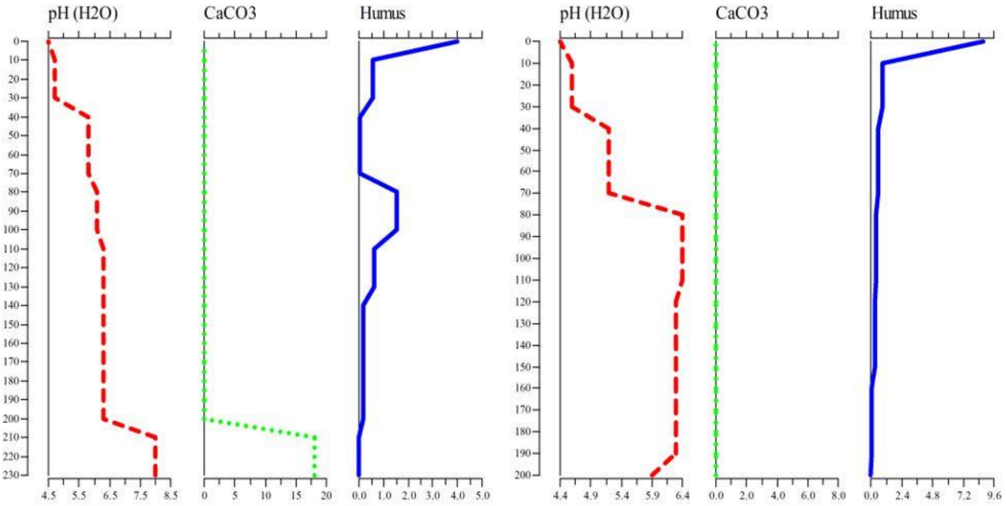

Figure 5. Distribution of soil pH_{H_2O}, $CaCO_3$ content and Humus% in profile 5 (left) and in profile 15 (right).

Three bark beetle species – *Tomicus piniperda, Ips sexdentatus*, and *Ips acuminatus* – were the most frequent in both trap tree cohorts. In some of the trees, *Tomicus minor* was also found in high numbers. While all trees of the first cohort were colonised, 5 out of 70 trees remained intact in the second cohort (*Table 3*). *T. piniperda* and *T. minor* colonised the trees first; they were followed by *I. sexdentatus* and *I. acuminatus*. We noted that there were some overlaps between the colonised tree parts. *I. sexdentatus* dominated the lower part of the trunk, *I. acuminatus* dominated the upper part of the trunk and the crown, including thicker branches. *T. piniperda* and *T. minor* excavated mother galleries in the trunk and in the crown, respectively.

Table 3. Bark beetle colonisation of the trap trees

Tree part	Bark beetle species	1st cohort (n=25)	2nd cohort (n=70)
Top (from crown base to the top)	*I. acuminatus*	6	56
	I. sexdentatus	3	10
	T. piniperda	–	3
	T. minor	14	–
Middle (crown base)	*I. acuminatus*	–	8
	I. sexdentatus	18	29
	T. piniperda	11	2
	T. minor	6	–
Trunk	*I. acuminatus*	–	–
	I. sexdentatus	21	42
	T. piniperda	23	–
	T. minor	–	–

Concerning bryological investigations, the largest population of *Campylopus introflexus* (5 dm^2) was found in a decayed *Pinus sylvestris* trunk in an open site. *Dicranum tauricum* is a new floral element in the *Pinus* study stand, and their populations have spread considerably in the last 30 years. We found all the 34 individual occurrences of these mosses, which live predominantly on decayed *Pinus sylvestris* trunks and logs. Some other new species were also collected on dead pine woods in the study area. These new species included *Nowellia curvifolia, Dicranum montanum*, and *Leucobryum juniperoideum*. In total, 102 bryophytes are known to live in the study area, of which 49 taxa were identified during the last decade, 32 species were confirmed, and 21 species of mosses were not found again (*Table 4*).

Table 4. Species richness of bryophytes, liverworts and mosses of the study area. "old": old records based on an early study (Purger 1992), and later not found; "old-new": species recorded by both bryological studies; "new": species recorded in latest fieldwork (Szűcs – Patocskai 2014), missing from earlier reference (Purger 1992).

Bark beetle species	old	old-new	new	total
Liverworts	0	1	5	6
Mosses	21	31	44	96
Total species number	21	32	49	102

The decreasing tendency of available water has a negative effect on tree ring widths (TRW). The TRW decreased in recent decades (since ~1990). Thus, we compared the climate datasets with the growth of tree ring widths. *Figure 6* shows the relative water capacity based on the Thornthwaite water balance model between 1961 and 2021. The connection between the previous year and the year of growth is represented with a 95 % confidence limit for the calculated parameters. The most intriguing fact in *Figure 6* is that despite the differences in age and soil characteristics, the physiological mechanisms in trees that are responding to environmental factors are basically the same. Generally, the available precipitation from June to August strongly influenced radial growth in the largest part of the observed period. June–August temperatures show a high negative effect on TRW. High summer temperature and intensive potential evapotranspiration influence significant negative effects on TRW values. Moreover, when the groundwater level started to decrease in the last 30 years, the correlation between the water level and radial growth began to decay, while at the same time, precipitation in May became more important. The correlation between the aridity index and TRW is not significant; this may explain that a high correlation between precipitation and TRW has not been observed. In Group I, the influences of the three selected parameters are stronger than in Group II.

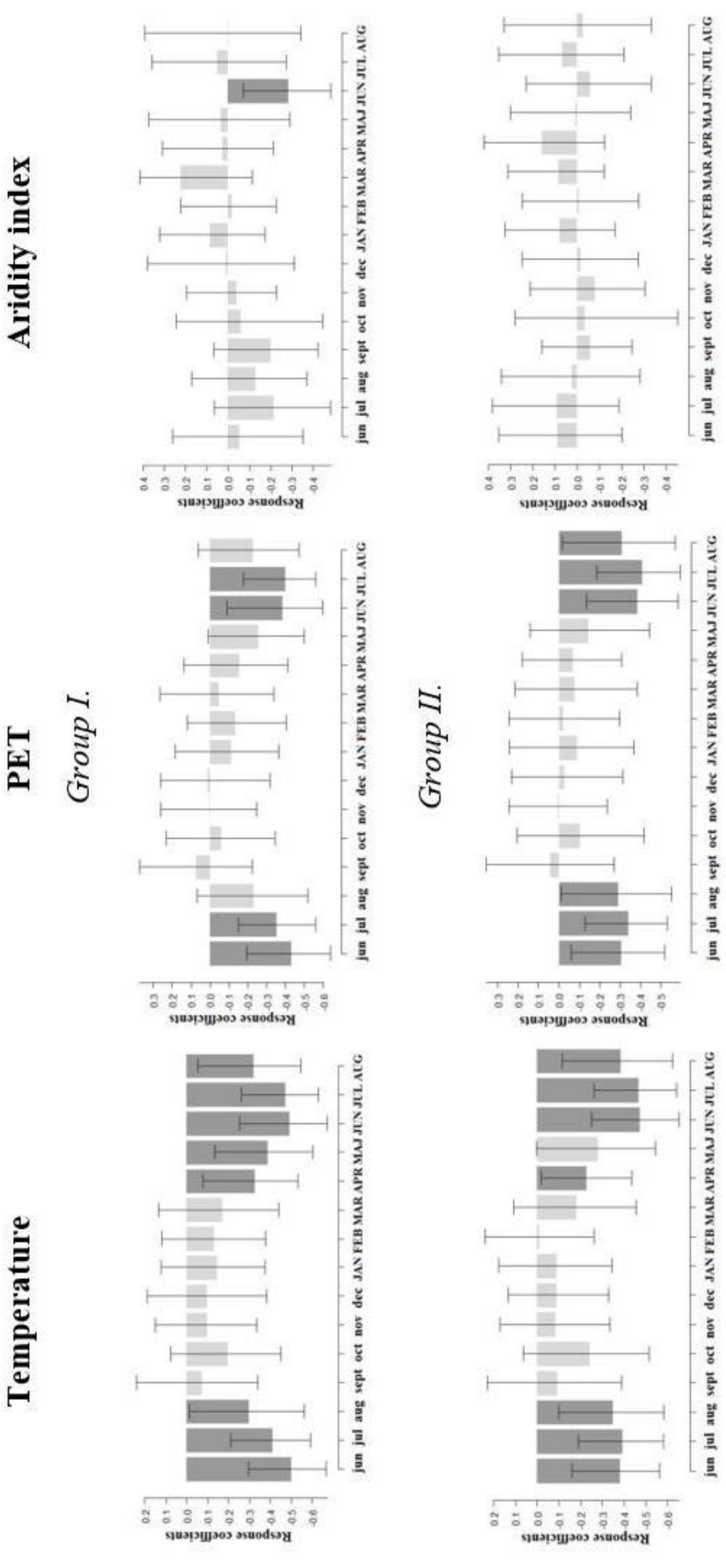

Figure 6. Results of Thornthwaite water balance model 1961–2021 was correlated with different climate parameters. Small letters representing the previous year and capital letters the year of growth. Light grey is the correlation values, where dark colour represents bootstrapped correlations significant at $p<0.05$, lower and upper lines represent 95 % confidence limit for the calculated parameters. Group I: discs from breast height, Group II: discs from root welling

4 DISCUSSION

Climate analysis shows that the increasing temperature, frequency of warm extremes, and recurring consecutive drought periods in the research area resulted in the poor health status of Scots pine.

Hardly any water is available for the species due to the shallow root zone and the scarce soil water storage. Water storage is poor even during extreme precipitation events. The frequency of drought periods and unfavourable soil conditions have reduced the relative water capacity of the soil. A Thornthwaite-type monthly water-balance model (Thornthwaite – Mather 1955) indicated that the water stress has increased significantly. We found decreasing TRW values caused by water stress in both old and young trees. The combination of temperature increases, precipitation decreases, and unfavourable sandy soils have likely caused the decrease in radial growth. The humic sand soils of the area absorb water relatively quickly, but it releases it just as quickly due to the physical variety of the soil. The maximum amount of water that can be stored in the soil is 100 mm. During drought periods (1990–1993; 2000–2003; 2011–2013), this soil type could not store enough water for vegetation. Moreover, the figure clearly shows the difference during very wet years (e.g., the year 2010), which could relieve plants from water stress. The measured TRW-s followed the monthly water balance model. Nevertheless, based on the TRW measurements, the TRW of older trees (> ~50 years) cannot increase their widths in wet years after the third drought period.

The acidic pH of topsoil (0-20 cm) is favourable for most tree species. The chemical properties of the soil are suitable for the vegetation, but the high $CaCO_3$ content of soils decreases soil productivity. Coarse sandy soils have low water storage capacity, and the water drains out from the upper layers rapidly. Therefore, water supply is scarcely available for vegetation (Stefanovits et al. 1999). Buried humus layers, which improve the water and nutrient supply of soils, were found in three soil profiles only (*Figure 6*). The low amount of total nitrogen, phosphorus, and potassium nutrients means that no part of this soil can store colloids.

Drought-induced mortality has occurred not only in the sandy soils of the study area but also in the entire area of Europe. High mortality of *Pinus sylvestris* has been observed in several places in the Swiss Alps (Rebetez – Dobbertin 2004). Drought was found to be the main limiting factor; however, the soil conditions were also unfavourable (rendzic leptosols, calcic), and in some cases, the calcareous sediment made soils even drier. The effects of a single, severe drought on TRW can be reversible, but a multi-year drought can reduce tree growth for several years and may lead to mortality (Bigler et al. 2006). Bauwe and colleagues (Bauwe et al. 2015) predicted a negative tendency of TRWs in north-eastern Germany towards the end of the 21st century.

A reclaimed area in northeast Estonia, where water deficit also occurs in summer (June–August) due to high temperature, provides another example; this variability is shown by the radial growth of Scots pine (Metslaid et al. 2016). Drought stress has been reported as a major factor in bark beetle attacks on Norway spruce (*Picea abies*) (Ježík et al. 2014). However, similar studies on Scots pine seem to be rare. The present study has shown that various bark beetle species are present in the area and drought stress makes weakened trees ideal candidates for bark beetle colonisation. We can make some notes and observations by comparing recent bryofloristical results (Szűcs – Patocskai 2014). New bryophyte species occur in the changing forest. The bryophytes do not contribute to the mortality of trees; however, they are indicators of health deterioration of the trees. The expanding (new and already present) species of mosses colonise the rotted wood, which accrued significantly with the increase of drought frequency. Fewer bryophyte species occurred due to the smaller amounts of rotted wood and less light. *Campylopus introflexus* is an invasive moss species in Europe (Hassel – Söderström 2005) that is expanding toward Eastern and South Europe (Alegro et al. 2018). The first Hungarian occurrence was discovered in NE-Hungary, about 60 kilometers from the study site in an old, declining *Pinus nigra* forest (Blockeel et al. 2007). Although Purger found no moss in 1992, (Purger 1992) the latest research has detected it in four localities. Further Hungarian occurrences have also been described in old pine forest stands where pine wood is available (Szűcs et al. 2014, Szűcs 2018).

The Bakonyerdő Ltd. (local forestry directorate) and the Faculty of Forestry (University of Sopron) jointly examined the climate, soil, and hydrological conditions of the area, as well as the entomological and plant pathological parameters, to uncover the potential direct and indirect causes of mortality. The unique landscape will change significantly despite these efforts because Scots pine will most likely disappear from the area. Based on our results, native deciduous tree species and sandy grassland habitats will develop in the sandy areas for the proposal of professionals and the decision support system.

5 CONCLUSIONS

This study aimed to provide a complex analysis to identify tree mortality causes in the only relict Scots pine forest in Hungary. We determined how site conditions have changed in the research area, which key factors were the most important, what kind of damages could occur, and how we could protect this vulnerable forest from decay. The meteorological data shows that the summer mean temperatures increased in the period 1961–2021. The frequency of extremely warm and dry periods and the total number of hot days increased significantly in recent decades. Increasing aridity can lead to higher water utilization and water reduction. These combined processes also had a negative influence on the radial growth of young and old pine trees. We found significant correlations between the decreasing TRW and the summer temperature.

Coarse sand texture is unfavourable to absorbing capacity. Water cannot be stored; thus, it leaches through the soil profile. Therefore, water is barely available to the trees, and the effect of high temperatures leads to increased evaporation. Warm winters help pests to survive. The appearance of bark beetles has started damage chains that lead to eventual mortality. The new invasive moss species displace native species and also damage the herbaceous level of the forest. Climate extremes and unfavourable soil properties affect the stand and induce a damage chain, where abiotic factors can cause secondary (biotic) damage to trees with reduced vitality. The light conditions in gaps within the forest are favourable to new invasive species (e.g., mosses or pests). The already observed impacts in the forest may be more severe in the future when threatening climate conditions are expected to be more frequent (Gálos et al. 2015). Therefore, Hungarian forest management must prepare strategies for the selection of adaptive tree species. This study recommends the following to forest managers:

1. Keep the water in forest areas to increase the groundwater level in ecosystem during prolonged drought periods if possible.
2. Promote mixed forests and close to nature forest management.
3. Take care of soil and consider the soil site properties before plantation.

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Impact Assessment of Trunk Injection and Bark Treatment in Black Cherry (*Prunus serotina* Ehrh.) Control

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Abstract – This invasive plant management study focuses on the treatment of younger and older seed-producing black cherry (*Prunus serotina* Ehrh.) individuals. We injected the older trees and applied bark treatment to the thinner saplings in 2018. Over two vegetation periods, we studied the effect of 11 herbicides and ranked the treatments based on their introduced foliage loss and sprouting. In the trunk injection experiment, the most effective treatment was a combination of glyphosate and clopyralid (Medallon Premium-Lontrel 300). Compositions without glyphosate did not meet expectations. In the bark treatment experiment, the herbicides used were combinations of glyphosate and MCPA (Medallon Premium Mecomorn-750 SL), glyphosate and dicamba (Medallon Premium-Banvel 480 S), and glyphosate and clopyralid (Medallon Premium-Lontrel 300). Results indicate that all three treatments are effective. Some of the technologies and chemical combinations this study presents are recommendable considering current plant protection legislation.

trunk injection / bark treatment / *Prunus serotina* / glyphosate / chemical control

Kivonat – A törzsinjektálás és törzskenés hatásának vizsgálata a kései meggy (*Prunus serotina* Ehrh.) elleni védekezés során. Növényvédelmi célú vizsgálatunkban magszóró, valamint fiatal kései meggy (*Prunus serotina* Ehrh). egyedek egyaránt kezelésre kerültek. Az idősebb fák injektálással, a vékony fiatal egyedek törzskenéssel való kezelése történt 2018-ban. Összesen tizenegy növényvédő szer hatását hasonlítottuk össze a két vegetációs időszakot felölelő kísérlet alatt, a kezelések a lombvesztés és a képződő sarjak alapján kerültek rangsorolásra. A törzsinjektálási kísérlet legeredményesebb kezelése a glifozát és klopiralid (Medallon Premium – Lontrel 300) kombinációja volt. A glifozátmentes szerek nem váltották be a hozzájuk fűzött reményeket. A törzskenés esetén az alkalmazott keverékek a glifozát és MCPA (Medallon Premium – Mecomorn 750 SL), a glifozát és dikamba (Medallon Premium – Banvel 480 S) valamint a glifozát és klopiralid (Medallon Premium – Lontrel 300) kombinációi voltak. Az eredmények alapján mindhárom kezelés sikeresnek tekinthető. A bemutatásra kerülő technológiák és szerkombinációk egy része a hatályos növényvédelmi jogszabályok figyelembevételével üzemi körülmények között is javasolhatók.

törzsinjektálás / törzskenés / *Prunus serotina* / glifozát / kémiai védekezés

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1 INTRODUCTION

Black cherry (*Prunus serotina* Ehrh.) was among the first species introduced to Europe from the Allegheny Plateau of the Appalachian Mountains in North America in the 17th century (Petitpierre 2008). According to Goeze (1916), black cherry appeared in Europe in 1629, while Wein (1930) states it was 1623. The first recorded occurrence in the Carpathian Basin was in 1897. Today, it is present in most European lowlands. The species was initially planted in the Netherlands (Van den Tweel – Eisjackers 1987) and Germany for fire protection and soil improvement purposes, typically on nutrient-poor sandy soils (Starfinger 1990, 1997; Muys et al. 1992, Starfinger et al. 2003, Kowarik 2010, Starfinger 2010, Terwei 2014). In its native environment, black cherry produces valuable lumber due to its extensive canopy and considerable height (Downey – Iezzoni 2000). It does not develop these attributes in European conditions (Petitpierre et al. 2009).

By the 1950s, foresters realized that black cherry had not met its expectations, and the damage the species caused quickly overshadowed the expected benefits (Muys et al. 1992). Kowarik (2010) provides a detailed analysis of the environmental and economic problems black cherry causes. The analysis states that dense canopies of black cherry inhibit the regeneration of native species. Black cherry reduces diversity in the herb layer due to its strong shading and the toxic cyanogenic glucosides (amygdalin, prunasin) found in its leaves and fruits (Schepker 1998, Brozdowski et al. 2021). Black cherry litter contains more nitrogen and other nutrients than the litter of most native European species (Vanderhoeven et al. 2005). This characteristic, combined with its observed allelopathic attributes (Csiszár 2009, Halarewicz et al. 2021), helps facilitate the spread of disturbance tolerant species by changing the nutrient composition of the soil (Chabrerie et al. 2008).

Black cherry seedling attributes include intense growth and strong sprouting ability (Marquis 1990). The intense growth and sprouting are due to its rootstock, which efficiently stores nutrients. Intense sprouting follows the felling of an adult tree; therefore, mechanical control methods rarely produce satisfying results (Annighöfer et al. 2012). The control method aims to destroy the root system, thereby eliminating the potential for sprouting. The trunk sprouting inherent in black cherry makes it hard to control the species. Uprooting and girdling are the most effective mechanical control methods. Due to the thick leaves, adhesives are advisable if chemical control becomes necessary (Csiszár – Korda 2017, Demeter – Lesku 2017).

Closed stands of black cherry increase the expenses of forest thinning, felling of diseased trees and end-use of forest stands by 40%. In addition, nurturing young forest stands can be ten times more expensive than usual (Borrmann 1988). A 2003 study assessed the damage caused by black cherry in German forests and reported annual crop failure and control costs of € 25 million (Reinhardt et al. 2003). Similar results appeared in the Netherlands (Olsthoorn – Van Hees 2002). Between 1997/1998 and 2007/2008, controlling black cherry in a biosphere reservation located in northern Italy accrued costs of 830,000 euros (Caronni 2008). The total cost of the various control methods of black cherry range from 150 to 1500 euro/ha/year. (Spaeth et al. 1994).

The main ingredient of the most frequently used herbicides to combat invasive plants in Hungary is glyphosate, and its use is always subject to authorization (Mihály 2017). Glyphosate has been in wide use since 1973, but in 2017, herbicides containing glyphosate were revised (Muys et al. 1992). Notwithstanding, in the same year, 18 members of the European Union (including Hungary) supported the authorization to use glyphosate for another five years. Nevertheless, enhanced analysis of glyphosate is overdue (Tosun et al. 2019).

This paper studied trunk injections, which – of all the chemical control methods in forestry – inflict the least damage on the environment. Properly executed bark treatment is also less polluting than the more commonly used spraying method. The herbicides studied in this experiment are reduced doses of successful mixtures previously used in 2016 (Nemes – Molnár 2017). The present study investigated the effectiveness of formulations devoid of glyphosate as well. The main goal of the experiment was to observe the effectiveness of the reduced doses to decrease the volume of herbicides released into the environment.

2 MATERIALS AND METHODS

2.1 Study site, location, and characteristics

We conducted the experiments in lands belonging to the Valkói Forestry of Pilisi Parkerdő Zrt. in the Gödöllő Hills forestry area of Hungary. The trunk injection experiment was performed in the Gödöllő 84/E (N – 47.56722, E – 19.36111); the bark treatment experiment was completed in the Gödöllő 84/C (N – 47.56111, E – 19.39944) forest subcompartments. These forest subcompartments are unmixed black locust (*Robinia pseudoacacia* L.) stands, in which black cherry manifests as an intensively spreading species. The mean annual precipitation level is 550-600 mm; the elevation of the forest subcompartment area of the experiments is 240-260 m. The mean annual temperature is 9.7 °C, and the annual sunlit hours are around 1,950 (OMSZ 2018). Neither forest subcompartment has any influx of water barring precipitation. According to the unified national soil type map (Pásztor et al. 2018), their soil types are humic sandy soils with surface soil depth between 60-90 cm (based on the forest subcompartments' description sheet).

Concerning climatic conditions, the second half of 2018 was a warm and dry season overall, with the second warmest autumn and the sixth warmest summer recorded in Hungary since 1901. There was a cold front at the beginning of October; otherwise, the mean temperature from July to December was higher than in most previous years. Heavy rainfall occurred on July 23, 2018 (over 6 mm mean for Hungary). Conversely, August was very dry, September was average, and the mean precipitation in October was far below average. Barely any rain fell in the first half of November. Humidity was higher in July, but from August to November, it was drier, while December was around the same humidity wise compared to the average of 1981-2010. (OMSZ 2018).

2.2 Selection of trees

We selected trees for the injection experiment according to two criteria:

1. The diameter at breast height (DBH) of trees must be above 5 cm, but most of the selected trees had diameters above 12 cm diameter at breast height.
2. The trees had to be healthy and full of foliage, especially the crowns.

Table 1 displays the mean diameter of the selected trees (with deviation) for the summer application of each treatment. *Table 2* contains the same information for autumn applications. Based on Kraft's crown class (Smith et al. 1997), the tables also exhibit the position distribution of treated trees in the canopy. The trees were between an estimated 20 and 30 years of age.

Table 1. The biometric parameters of the injected trees of experiment conducted on July 25

Treatment	Mean diameter at breast height (cm)	Deviation	Crown class (Kraft)			
			D	CD	I	S
1.	13.6	5.1		2	1	7
2.	12.9	5.3		6		4
3.	18.3	4.3	1	9		
4.	15.5	5.4		9		1
5.	12.1	5.5		7	1	2
6.	15.5	2.3		10		
7.	17.4	4.0		10		
8.	18.3	5.9		6	1	3
9.	18.5	8.9		7		3
10.	16.5	5.2		8	1	1
11.	19.8	4.6		9		1

Abbreviations: For Crown class: D = Dominant, CD = Codominant, I = Intermediate, S = Suppressed. The numbers in the "Crown class (Kraft) column display the number of trees that fall into each category by each treatment. For treatments see *Table 5.*

Table 2. The biometric parameters of injected trees of the experiment conducted on Sept. 15

Treatment	Mean diameter at breast height (cm)	Deviation	Crown class (Kraft)			
			D	CD	I	S
1.	13.4	7.1		2		8
2.	19.4	12.6	1	5	1	3
3.	15.5	8.1	1	3		6
4.	12.8	6.5		4		6
5.	18.6	8.6	1	8		1
6.	16.8	6.4		2	1	7
7.	16.6	5.0		5	2	3
8.	15.9	9.3		3	2	5
9.	14.3	6.8		2	1	7
10.	14.5	7.4		2	1	7
11.	15.3	6.0		2	1	7

Abbreviations: For Crown class: D = Dominant, CD = Codominant, I = Intermediate, S = Suppressed. The numbers in the "Crown class (Kraft) column display the number of trees that fall into each category by each treatment. For treatments see *Table 5.*

For the bark treatment experiments, we selected trees according to one criteria: They had to be healthy and have intact foliage. The trees on that plot were similar, but most black cherry specimens were healthy. *Table 3* and *Table 4* list the treated tree diameters for the summer and autumn application respectively. We estimated the trees were around 5–8 years old.

Table 3. Mean diameter at breast height (cm) of treated trees of the experiment conducted on July 25

Treatment	Mean diameter at breast height (cm)	Deviation
1.	4.3	1.2
2.	4.5	1.1
3.	4.6	1.1

For treatments see *Table 6.*

Table 4. Mean diameter at breast height (cm) of treated trees of the experiment conducted on September 15

Treatment	Mean diameter at breast height (cm)	Deviation
1.	4.4	1.2
2.	4.6	1.2
3.	4.7	1.2

For treatments see *Table 6.*

2.3 Applied treatments and herbicides

We chose the herbicides and doses based on our previous experiences with projects that included defence against black cherry (Nemes 2015, Nemes – Molnár 2017), and on the recommendations of invasive plant management specialists who previously used part of these products (Demeter – Lesku 2017, Verő – Csóka 2017).

We performed the experiments on July 25, 2018, and on September 15, 2018. We applied 11 treatments during the trunk injection experiment (*Table 5*) on two occasions. We injected the trunks of 10 specimens on both occasions. We treated 220 specimens in total.

During the trunk injection experiment, we treated trees with formulations and the mixtures listed in *Table 5.* All treatments were 55% concentration aqueous solutions, except for the eighth treatment. Medallon Premium, the main herbicide used in this experiment, is widely used in forest plant protection. Consequently, we tested this herbicide by itself as the first treatment. In treatments 2–5, we mixed Medallon Premium with other components (Mecomorn 750 SL, Banvel 480 S, Lontrel 300, Tomigan 250 EC). We added formulations containing good quality translocating ingredients to the mixtures. One of the components of the eighth treatment contained glyphosate but also consisted of a 2.4-D active substance.

Table 5. Used herbicides during injection

Treatment	Formulation	Dosage	Active substance
1.	Medallon Premium	55%	480 g/l glyphosate
2.	Medallon Premium	50%	480 g/l glyphosate
	Mecomorn 750 SL	5%	750 g/l MCPA
3.	Medallon Premium	50%	480 g/l glyphosate
	Banvel 480 S	5%	480 g/l dicamba
4.	Medallon Premium	50%	480 g/l glyphosate
	Lontrel 300	5%	300 g/l clopyralid
5.	Medallon Premium	50%	480 g/l glyphosate
	Tomigan 250 EC	5%	36% fluroxypyr
6.	Chikara Duo	55 %	6.7 g/kg flazasulfuron + 288 g/kg glyphosate
7.	Kyleo	55%	160 g/l 2.4 D + 320 g/l glyphosate
8.	Kyleo	40%	160 g/l 2.4 D + 320 g/l glyphosate
	Mezzo 20 WG	1%	20% metsulfuron-methyl
9.	Mecomorn 750 SL	55%	750 g/l MCPA
10.	Banvel 480 S	55%	480 g/l dicamba
11.	Lontrel 300	55%	300 g/l clopyralid

The bark treatment experiment had three treatments (*Table 6*), and we performed this experiment two times. We applied each treatment to 15 tree specimens both times and treated 90 specimens in total. Formulations and mixtures used in the bark treatment were reduced doses of what we utilized in the trunk injection experiment. Contrary to a previous experiment (Nemes – Molnár 2017), we did not use linseed oil as a solvent but chose lesser viscosity water instead.

Table 6. Used herbicides during bark treatment

Treatment	Formulation	Dosage	Active substance
1.	Medallon Premium Mecomorn 750 SL	30% 3%	480 g/l glyphosate 750 g/l MCPA
2.	Medallon Premium Banvel 480 S	30% 3%	480 g/l glyphosate 480 g/l dicamba
3.	Medallon Premium Lontrel 300	30% 3%	480 g/l glyphosate 300 g/l clopyralid

We drilled multiple holes (2–5, depending on the treated tree's diameter at breast height) 5 centimetres apart into the thicker, bearing specimen trunks at breast height. The hole diameters were 6 millimetres, their depth was 2.5 centimetres, and their angle was 45° degrees. We injected 1 ml of each formulation directly into the sapwood, after which we closed the holes with silicone acetate to prevent leaching and evaporation.

Three people executed the injection. The first person drilled the holes; the second person injected the formulations; the third person plugged the holes using a caulking gun. Treating a tree took no more than one minute and ensured minimal mixture evaporation. We marked injected trees with an airbrush for subsequent identification. We evaluated the injected trees and observed the damage inflicted on the injected specimens.

The experiment treated 2–5 cm-thick young trees with heights between 2–3 m. Procedure execution consisted of treating the full girth of the trees with the formulations 1 m above ground clearance in 30–40 cm wide lines. We used a brush to apply the formulations.

2.4 Evaluation of treatment efficiency

We classified the tested technologies that resulted in the destruction of black cherry – both the above and underground parts – as successful. Foliage loss determined the aboveground destruction. We examined the colour change and drying of the foliage in the total ratio of the tree crown and assessed foliage loss visually without considering the leaves on the emerging sprouts.

To demonstrate the drying of foliage, we used a scale ranging from 1 to 10 (*Table 7*). Although EPPO's (2014) phytotoxicity assessment standard influenced our thought process, we created the scale mostly from our own experiences. We wanted to demonstrate the phytobiological effects of the applied herbicides at a deeper level than just foliage loss and created the values for statistical comparison. We chose the 1–10 scale to make comprehension easily accessible and comprehensible. We distinguished between brown and dry foliage based on the water content of the tissues; leaves deemed as brown had much higher water content than dry leaves. The foliage of each treated specimen was assessed separately. The values were weighted based on the percentage of the foliage representing each condition. We then added up the observed conditions. For example, if one injected tree had foliage that was 40% yellow but 60% was visibly completely dry, it would have a value of 6.7, based on this calculation: $0.4 \times 4 + 0.6 \times 8.5 = 6.7$.

Table 7. The scale created to demonstrate the efficiency of the treatments

Value	Foliage condition
1	Foliage is 100% green, undamaged and viable
4	Foliage is 100% yellow
7	Foliage is 100% brown
8.5	Foliage is completely dry
10	Total foliage loss

We could infer the degree of the root destruction by reduced re-sprouting ability and sprout vitality; an absence of sprouts indicated destruction.

We conducted two-week evaluations of the experiment we conducted on July 25, 2018. These evaluations lasted until October 8, 2018. The experiment conducted on September 15, 2018, was assessed on September 29, 2018, which was the only assessment during the vegetation period. The evaluations stopped on these dates to avoid misidentifying loss of foliage due to the treatments for winter abscission of foliage. We assessed both experiments once more on May 5, 2019, in the following vegetation season. We rated the treatments based on foliage condition and the number of sprouts that appeared by May 5, 2019. We did not measure sprouts that treated trees produced because every injected tree produced them in such a great quantity (over 20/tree, estimated) and quality (over 40 cm height/sprout, estimated). Nonetheless, we assumed the sprouts were not only sufficient to ensure the survival of the treated tree but also concluded that they actively furthered the colonization of black cherry. We did not calculate final foliage loss during 2018 but completed observations on May 5, 2019.

To reveal the differences between each treatment regarding leaf loss alone, we evaluated the results via non-parametric ANOVA (Kruskal-Wallis test) ($P < 0.05$) based on the foliage loss observed on May 5, 2019 (InStat 2003).

3 RESULTS

3.1 Results of the trunk injection experiment

We compared the results of the injection experiment. The Kruskal-Wallis test did not show a significant difference between the formulations containing glyphosate ($P>0.05$, KW = 169.03). However, there was a disparity between the herbicides containing glyphosate and those that did not. Significant distinction occurred between concoctions including glyphosate and Mecomorn 750 SL ($P < 0.05$, KW = 169.03), and an extremely significant difference appeared between glyphosate mixtures, and Banvel 480S, Lontrel 300 ($P < 0.001$, KW = 169.03) as well.

There was no contrast between Mecomorn 750 SL and Banvel 480S ($P > 0.05$, KW = 169.03), but there was an extremely significant difference between Mecomorn 750 SL and Lontrel 300 ($P < 0.001$, KW = 169.03), and an enormous difference between Banvel 480S and Lontrel 300 ($P < 0.01$, KW = 169.03).

Figure 1 shows the effect of each herbicide applied on July 25, 2018. *Figure 2* exhibits the effect of the formulations of *Figure 1* that did not stimulate sprouting. *Figure 3* contains the effect of the herbicides of the second application. *Figure 4* shows those herbicides in *Figure 3* that did not trigger sprout production.

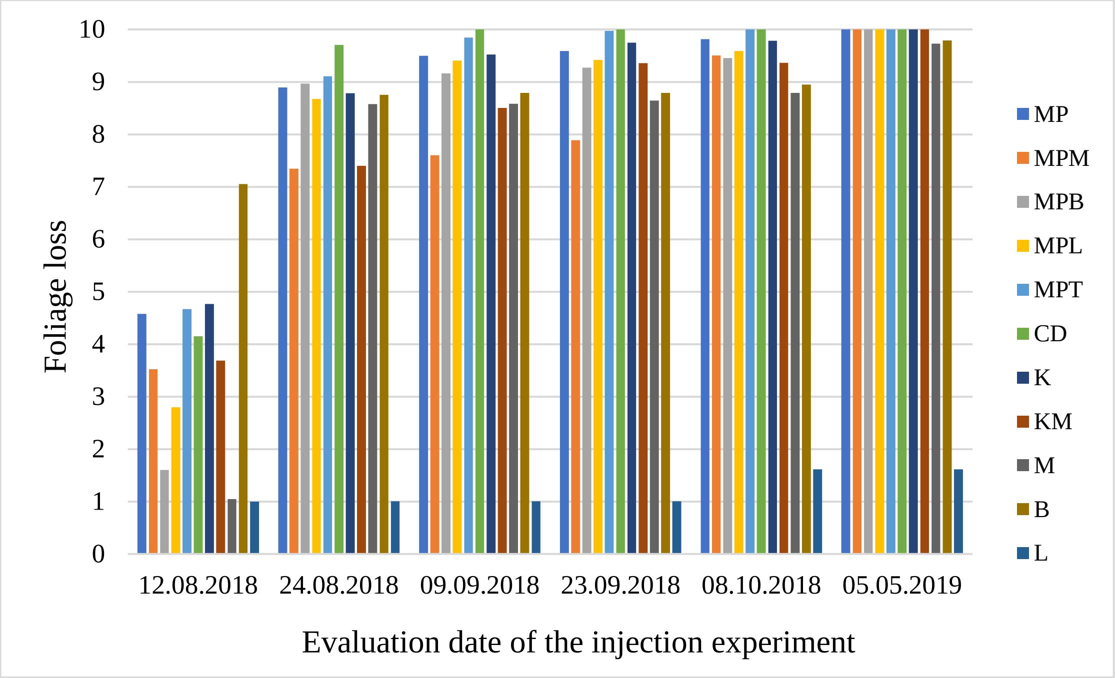

Figure 1. Effectiveness of formulations used in the trunk injection experiment conducted on July 25. MP: Medallon Premium, MPM: Medallon Premium - Mecomorn 750 SL, MPB: Medallon Premium - Banvel 480 S, MPL: Medallon Premium - Lontrel 300, MPT: Medallon Premium - Tomigan 250 EC, CD: Chikara Duo, K: Kyleo, KM: Kyleo – Mezzo 20 WG, M: Mecomorn 750 SL, B: Banvel 480 S, L: Lontrel 300

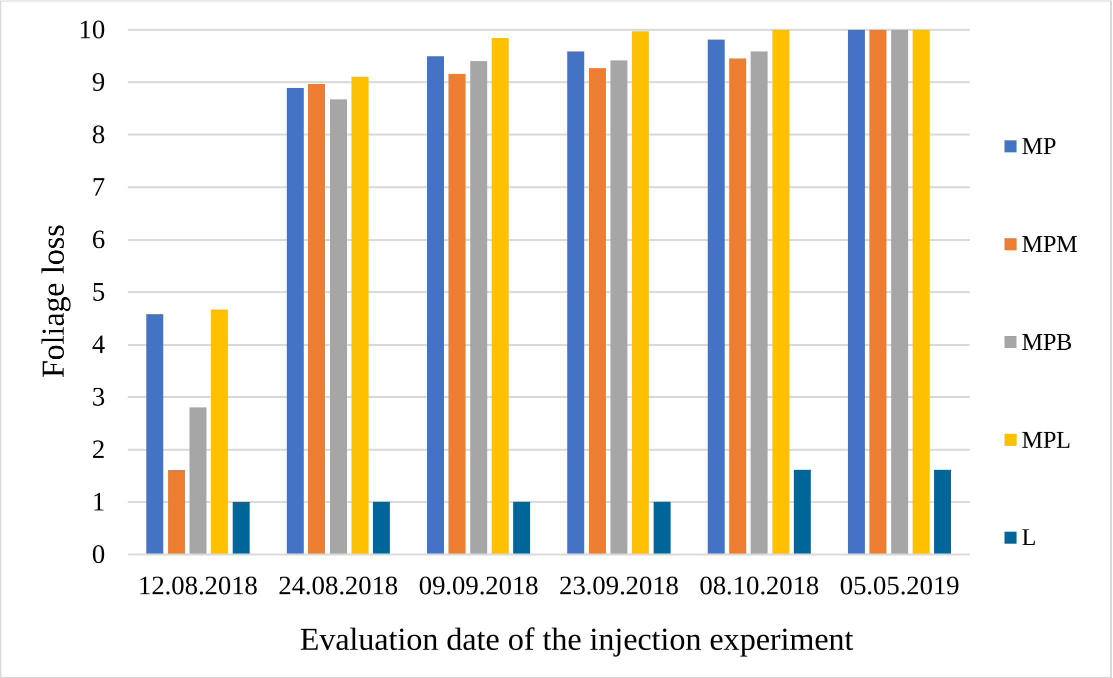

Figure 2. Effectiveness of the formulations used in the trunk injection experiment conducted on July 25 that did not stimulate sprouting. Abbreviations: see Figure 1.

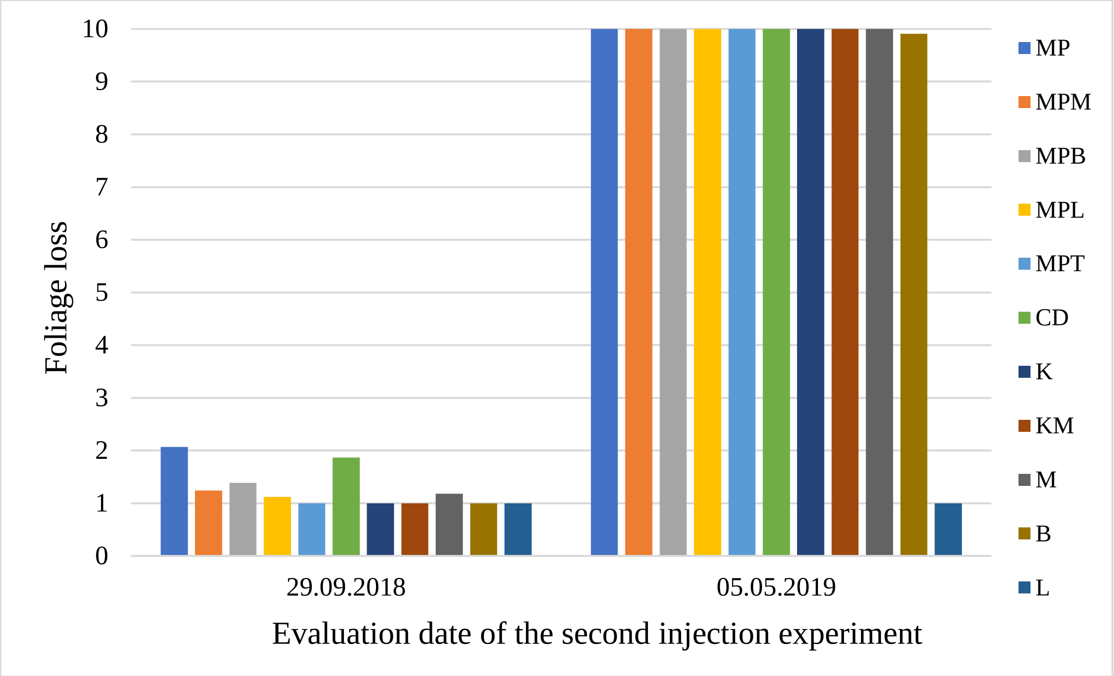

Figure 3. Effectiveness of formulations used in the trunk injection experiment conducted on September 15. Abbreviations: see Figure 1.

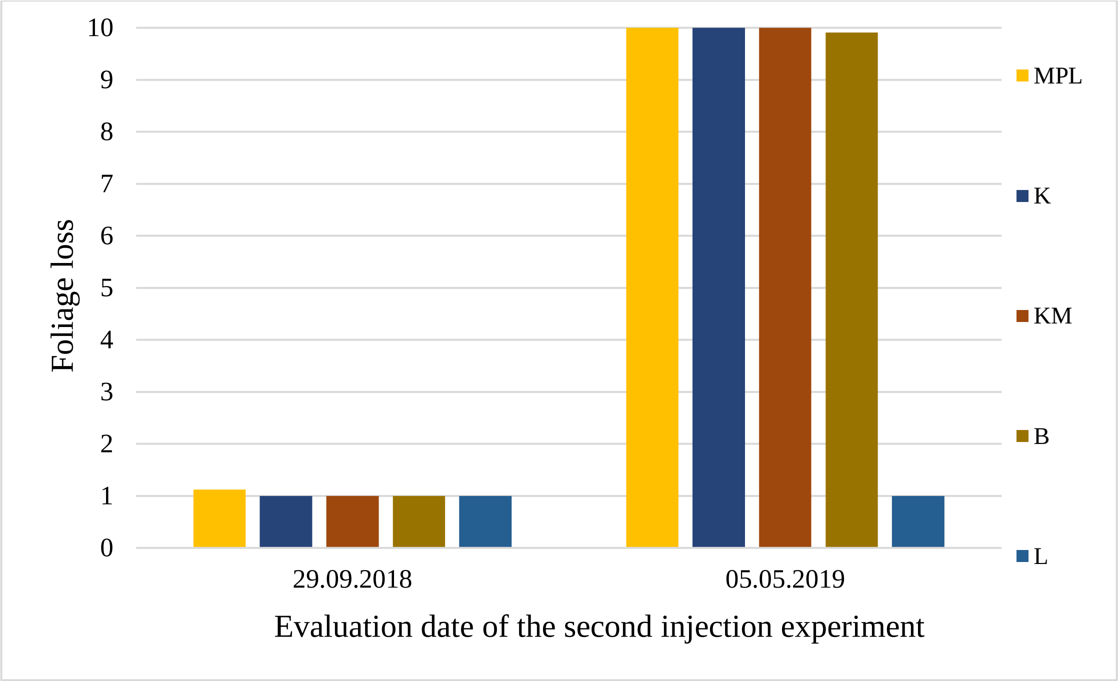

Figure 4. Effectiveness of the formulations used in the second trunk injection experiment conducted on September 15, that did not stimulate sprouting. Abbreviations: see Figure 1.

Table 8 ranks the formulations based on induced foliage loss and sprout stimulation. The values of the final date in the table are the mean of both the first and second trunk injection experiment.

Overall, the best mixture was the 50–5% aqueous solution of Medallon Premium – Lontrel 300 (480 g/l glyphosate-300 g/l clopyralid) combination, which was effective when applied in both summer and autumn. Moreover, it stimulated no sprouting in either case.

The following three treatments could potentially be applied in summer without stimulating sprouting. Ranked from best to worst, these include Medallon Premium-Tomigan 250 EC (480 g glyphosate-36% fluroxypyr), Medallon Premium (480 g glyphosate), and Medallon Premium-Banvel 480 S (480 g/l glyphosate-480 g/l dicamba).

The following three combinations could be applied in autumn without stimulating sprouting. From best to worst, these were Kyleo (160 g/l 2.4-D + 320 g/l glyphosate), Kyleo – Mezzo 20 WG (160 g/l 2.4-D + 320 g/l glyphosate-20% metsulfuron-methyl), and Banvel 480 S (480 g/l dicamba).

The following four treatments were unsuccessful. The first three stimulated sprouting, and the fourth had an insufficient effect on foliage loss: Chikara Duo (6.7 g/kg flazasulfuron + 288 g/kg glyphosate), Medallon Premium – Mecomorn 750 SL (480 g/l glyphosate-750 g/l MCPA), Mecomorn 750 SL (750 g/l MCPA), and Lontrel 300 (300 g/l clopyralid).

Table 8. The effectiveness of each treatment of the injection experiment according to the foliage loss and sprouting, ranked from best to worst

	Evaluation of the injection according to the foliage loss						Sprouting	
Treatment	201.8. 8.12	2018.08.24	2018.09.09	2018.09.23	2018.10.08	2019.05.05	1st application	2nd application
MP- Lontrel 300	2.8	8.7	9.4	9.4	9.6	10.0	-	-
MP - Tomigan 250 EC	4.7	9.1	9.8	10.0	10.0	10.0	-	Yes
MP	4.6	8.9	9.5	9.6	9.8	10.0	-	Yes
MP - Banvel 480 S	1.6	9.0	9.2	9.3	9.5	10.0	-	Yes
Kyleo	4.8	8.8	9.5	9.7	9.8	10.0	Yes	-
Kyleo - Mezzo 20 WG	3.7	7.4	8.5	9.4	9.4	10.0	Yes	-
Banvel 480 S	7.1	8.8	8.8	8.8	9.0	9.9	Yes	-
Chikara Duo	4.2	9.7	10.0	10.0	10.0	10.0	Yes	Yes
MP - Mecomorn 750 SL	3.5	7.3	7.6	7.9	9.5	10.0	Yes	Yes
Mecomorn 750 SL	7.1	8.8	8.8	8.8	9.0	9.9	Yes	Yes
Lontrel 300	1.0	1.0	1.0	1.0	1.6	1.3	-	-

Abbreviations: MP: Medallon Premium. Foliage loss were calculated according to *Table 7.*

3.2 Results of the bark treatment experiment

In the bark treatment experiment, combinations Medallon Premium-Mecomorn 750 SL, Medallon Premium-Banvel 480 S initially showed better results than the Medallon Premium-Lontrel 300 formulation (*Figure 5*). Loss of foliage proceeded faster in the first two treatments mentioned above, and there was visible drying during the second evaluation in August. While in the case of Medallon Premium-Lontrel 300 mixture, the rate of foliage loss was slower and strong green shoots were present.

However, at the final evaluation, we observed that all three treatments resulted in total loss of foliage, and only one of 15 trees treated with Medallon Premium-Mecomorn 750 SL produced two sprouts. Therefore, we derived that all three treatments can be considered successful.

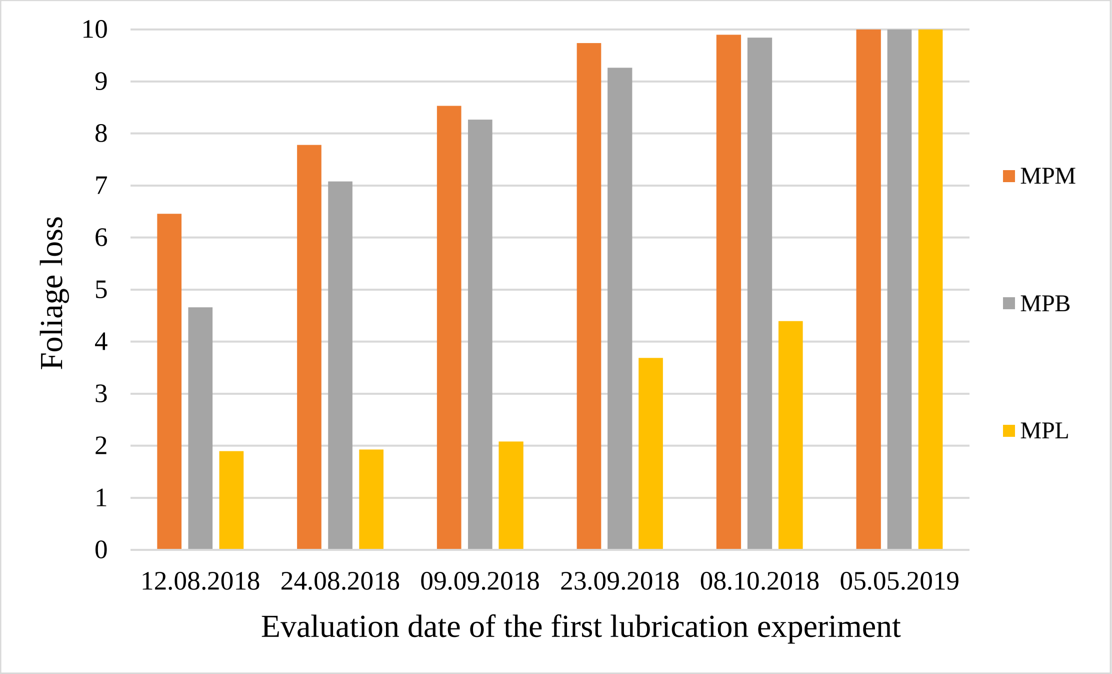

Figure 5. Effectiveness of formulations used in the bark treatment experiment conducted on July 25. Abbreviations: see Figure 1.

The second iteration of the experiment greatly resembled the first one detailed above (*Figure 6*), but no sprouts appeared this time.

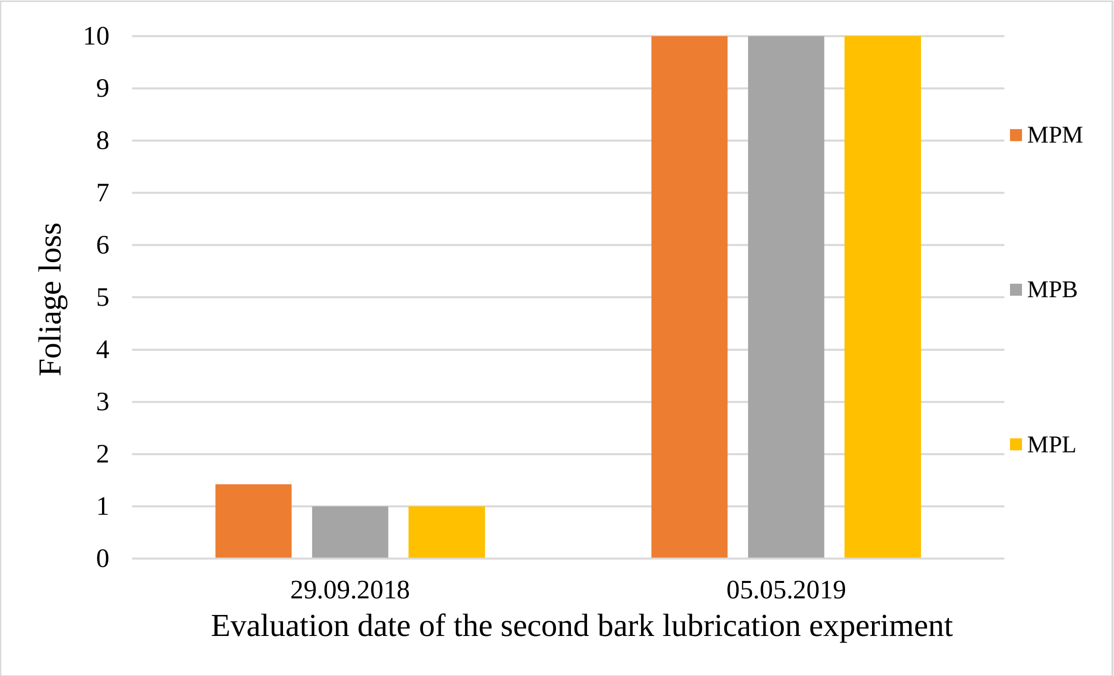

Figure 6. Effectiveness of formulation used in the bark treatment experiment conducted on September 15. Abbreviations: see *Figure 1.*

All treated trees were leafless and virtually sprout-less (see above) at the final evaluation. Consequently, there was not much point in conducting a Kruskal-Wallis test as we did in the trunk injection experiment.

4 DISCUSSION

The most commonly used procedure to suppress black cherry is the cut-stump method, in which after the felling of black cherry, herbicides are applied in an attempt to inhibit its growth (Lemmens – Tol 1977; Brehm 2004; Vanhellemont et al. 2008). Otręba et al. (2017) found this method ineffective. However, they found mechanical girdling to be an effective method.

Not all treatments were successful in the trunk injection experiment. The differences manifested in the time needed to show effects and the influence on sprouting ability. The formulations tested were not always fruitful in their respective doses. Nevertheless, those that were effective could potentially be used in practice, especially the combination of glyphosate and clopyralid (Medallon Premium-Lontrel 300). The combinations whose applications resulted in intense sprouting despite the destruction require attention; the season of planned application needs to be considered to avoid the undesirable sprouting response (*Table 8*). The soil was moderately fertile, but on weaker soils, there would be potentially less sprouting response because the trees would have fewer reserve nutrients stored. The reverse applies to soils that are more fertile. One of the most important aspects of all control methods is their effect on the environment, which entails that we need to favour mechanical methods whenever possible. However, mechanical methods do not always yield the outcomes expected of them in practice. According to a Polish experiment (Otręba et al. 2017), girdling – which is the most successful mechanical method – only destroyed 24–54% of treated trees. A Belgian study calls attention to the varying efficiency of mechanical methods, citing that even though biological methods can be very successful, the reliability of these methods drops off compared to chemical methods (Van Den Meersschaut – Lust 1997). Moreover, executing biological methods properly requires great expertise. Wronska-Pilarek et al. (2022) emphasise that chemical control is successful in reducing inflorescence size and number. Mechanical methods are always preferred in nature conservation areas because glyphosate and other chemicals endanger valuable local flora. Still, it is important to clarify the minimum effective doses of each chemical because in the areas where chemical control is unavoidable, it must be done in the gentlest way possible.

Glyphosate-based herbicides are the mostly widely used herbicides worldwide and in Hungary. Their use is always subject to authorization (Mihály 2017). Opinions regarding glyphosate differ, and its toxicity is controversial. Rolando et al. (2017) has found that glyphosate-based herbicides applied correctly in a prescribed manner cause no significant concerns for humans, land, or aquatic fauna. In contrast, in their systematic literature review, Brovini et al. (2021) concluded that glyphosate represents a high risk to aquatic environments when applied at the concentrations permitted by the legislation of some countries. Another study found that the reported toxic effects are not from the glyphosate itself, but originate from the petroleum-based oxidized molecules (POEA) (Defarge et al. 2018). However, Van Bruggen et al. (2018) have warned that while the acute toxic effects of glyphosate are low, exposure to chronic, ultra-low doses due to its accumulation in the environment has significant environmental risks. Even though their critical review does not attribute a clear and unambiguous harmful effect to glyphosate, Torretta et al. (2018) have argued that glyphosate use should be reduced.

The experiment with reduced dosage was not as conducive as we had hoped for ecological and economic reasons. Overall, we found both trunk injection and bark treatment to be effective control methods, viable to use after a meticulous risk assessment, reinforcing previous literature (Csiszár – Korda 2017; Demeter – Lesku 2017, Nemes – Molnár 2017, Verő – Csóka 2017).

All three formulations were efficient in the bark treatment experiment; they all resulted in 100% destruction of the treated specimens. There were some differences in their effect-causation process. An important result is that even though there was no mechanical pre-treatment, all treated trees were still destroyed. We can conclude that bark treatment using the appropriate formulations and a simple paintbrush is sufficient. This is noteworthy concerning the method process because bark treatment is easier and faster than injection.

5 CONCLUSIONS

Our results confirm that trunk injection and bark treatment can be effective control methods when executed with herbicides that do not stimulate sprouting. These results accord with the results of earlier studies (Demeter – Lesku 2017, Nemes – Molnár 2017, Verő – Csóka 2017). Mechanical methods are still preferable whenever possible, but these methods are not always effective. Moreover, biological methods are often uncertain, even when executed with great care and knowledge. Since most habitats include young, middle-aged, and old trees simultaneously, using all three control methods carefully would be ideal to minimize environmental impact yet yield good results. In areas where control of black cherry is unsuccessful barring the application of herbicides, knowledge of minimum effective doses is essential to minimize potential negative effects on the environment.

Due to significant sprouting, we believe that conducting further experiments regarding dose reduction in stands of similar habitats holds no benefit. Even when the seed-producing specimens were destroyed, the destruction was accompanied by vigorous sprouting, which created a problem tantamount to the one we were trying to solve. In our case, the sprouts were abundant and vigorous enough to ensure the further spread of the species.

Formulations containing glyphosate showed significantly better results than formulations that did not contain the substance. However, one treatment which did not have glyphosate as its active component, Banvel 480 S (480 g/l dicamba), was successful when applied in autumn. Further experiments could focus on this treatment to study its effectiveness because if it is effective, it could be used instead of glyphosate.

Treating the bark of young trees or individuals with a thin trunk using a brush is sufficient to ensure extermination. This is an important result because a simple technology such as just drawing lines with a brush alone can treat more trees over the same course of time as opposed to making a wound on a tree in addition before applying the herbicide with a brush.

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Inter- and Intraspecific Differences in Physical and Mechanical Properties of Wood from *Sclerocarya birrea* and *Anogeissus leiocarpus*

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Abstract – This paper studied the basic density and mechanical properties differences of wood among and within *Sclerocarya birrea* and *Anogeissus leiocarpus*. Three trees from each species were selected from the Lagawa Natural Forest Reserve in Western Kordofan State, Sudan. Test specimens were selected from three vertical positions (10, 50, and 90% along the bole length) of the trees. Specimens were also collected from three horizontal positions (innerwood, middlewood, and outerwood) within each of the three vertical positions. Tests for basic density of wood (BD), modulus of rupture (MOR), modulus of elasticity (MOE), compressive (CS), and shear strength (SS) parallel to the grain were performed. An analysis of variance shows that only the horizontal positions were a significant source of variation for both species studied. The correlation coefficient of BD was significant, weak, and positive for the mechanical properties of *A. leiocarpus.* A similar observation was found for BD correlated with CS and SS for *S. birrea*.

***Sclerocarya birrea* / *Anogeissus leiocarpus* / basic density / strength / modulus of elasticity**

Kivonat – A *Sclerocarya birrea* és az *Anogeissus leiocarpus* fafajok közötti és fafajon belül kimutatható eltérések a faanyag fizikai és mechanikai tulajdonságaiban vonatkozásában. A kutatásban vizsgáltuk a *Sclerocarya birrea* és az *Anogeissus leiocarpus* faanyagok bázis sűrűségének és mechanikai tulajdonságainak változásait a két fafaj között és a fafajokon belül. Minden fajhoz három faegyedet választottunk ki a szudáni Nyugat-Kordofan állambeli Lagawa Természeti Erdőrezervátumból. A próbatesteket három függőleges helyzetből (10, 50 és 90%-ban a törzshossz mentén) választottuk ki a fákon belül. Ezenkívül a mintákat három vízszintes helyzetből (belső farész, középső farész és külső faszövet) gyűjtöttük a három függőleges pozíció mindegyikén belül. Meghatároztuk a faanyag bázis sűrűségét (BD), vizsgáltuk továbbá a rostiránnyal párhuzamos hajlító szilárdságot (MOR), rugalmassági modulust (MOE), nyomószilárdságot (CS) és nyírószilárdságot. A varianciaanalízis azt mutatja, hogy mindkét vizsgált faj esetében csak a vízszintes helyzet mutatott jelentős eltérést. Az *A. leiocarpus* mechanikai tulajdonságai statisztikailag szignifikáns, de gyenge

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korrelációt mutattak a bázis sűrűséggel. A sűrűség növekedésével a szilárdságok is nőttek. A *S. birrea* fafajnál hasonló megfigyelést mutattunk ki, a sűrűség növekedésével nőtt a nyomó- és a nyírószilárdság.

***Sclerocarya birrea* / *Anogeissus leiocarpus* / bázis sűrűség / szilárdságok / rugalmassági modulusz**

1 INTRODUCTION

Wood is a natural material with many utilization purposes (Desch – Dinwoodie 1996). The distinctive features of wood (anisotropic, hygroscopic, orthotropic, and renewable) make it an easily recognizable material (Koch 1985). Generally, cellulose, hemicelluloses, and lignin ratios differ in wood components (Panshin – de Zeeuw 1980) between species. Moreover, these components vary between hardwood and softwood trees (Shmulsky – Jones 2011).

Several factors – including genetics, environment, site, age, and defects – contribute to wood variability (Desch – Dinwoodie 1996). These factors lead to the variation in the anatomical, physical, and mechanical properties of wood (Shmlusky – Jones 2011), which frequently weakens the acceptance of wood as a structural material (Desch – Dinwoodie 1996).

Variations in the physical and mechanical properties of wood among and within tree species have been extensively studied (Karki 2001, Steffenrem et al. 2007, Knapic et al. 2008, Chowdhury et al. 2009, Al-Sagheer – Prasad 2010, Chowdhury et al. 2013, Majumdar et al. 2014, Kiaei et al. 2015, Kiaei – Farsi 2016, Wessels et al. 2016, Xie et al. 2017 and Bektaş 2020). A previous study in Sudan revealed no significant source of variations in basic density within the wood of *Balanites agyptiaca* (Awad 2015). However, significant sources of variations in wood density were found within *Tectona grandis* wood (Izekor et al. 2010). Wood variability attributed to variations between sites has been studied among *Pinus sylvestris* and *Acacia melanoxylon* in Portugal (Fernandes et al. 2017, Machado et al. 2014).

Sclerocarya birrea belongs to the Anacardiaceae family and can grow up to 12 m high (Vogt 1995). The wood is traditionally used for carving, furniture, saddles, and locally for manufacturing. Presently, the species is still important for sustaining rural livelihoods (Sahni 1968). In Sudan, *Sclerocarya birrea* can be found in places such as Kassala, Imatong Mountains, Erkwit, Blue Nile, Kordofan, and Darfur. The wood of *Sclerocarya birrea* is soft, diffuse-porous, and low to medium in density. The color of freshly cut wood is grayish with reddish bands and streaks, brown patches, and delivered to darkening reddish brown. The sapwood has been described as very wide, and it is not sharply differentiated from the heartwood (Goldsmith – Carter 1981).

Anogeissus leiocarpus (African birch) belongs to the Combretaceae family and can grow to a height of up to 20 m. Its wood has been locally used for transmission and building poles, fence posts, and forked poles. It is also used for beams in rural building construction. With its high energy characteristics, it is also used as firewood and for charcoal production. In Sudan, *Anogeissus leiocarpus* is found along streams and rivers and in valleys in South Kassala, Kordofan, South Darfur, and the Blue Nile states (El Amin 1990). The wood of *A. leiocarpus* is grayish outside, dark brown at the heart and very hard. The wood is ring porous and contains surface crystals and traumatic ducts (Ayeola et al. 2009).

Adequate scientific information on the technical properties of these two Sudanese species could lead to effective promotion and efficient utilization of their wood. The objective of this research was to investigate the variability of wood along the height of a tree and horizontal positions (innerwood, middlewood, and outerwood). The specific traits considered are basic density (BD), modulus of rupture (MOR), modulus of elasticity (MOE), compressive strength parallel to the grain (CS), and shear strength parallel to the grain (SS) within and among *S. birrea* and *A. leiocarpus* trees.

2 MATERIALS AND METHODS

2.1 Materials

Three trees each for species of *Sclerocarya birrea* and *Anogeissus leiocarpus* were randomly selected for the study. The trees were growing naturally in Lagawa Natural Forest Reserve located in the Western Kordofan State, Sudan, between 11°24′20″N - 29°8′18″E (Fig. 1). The trees were straight and free from natural defects. *Table 1* provides the basic morphological description of the sampled trees.

Table 1. Diameter at breast height (dbh), tree height and bole length for Sclerocarya birrea and Anogeissus leiocarpus

Species	Tree No.	Dbh (cm)	Tree height (m)	Bole length (m)
S. birrea	1	40	13	2.0
	2	42	16	2.5
	3	47	17	3.5
A. Leiocarpus	1	35	16	2.0
	2	38	15	2.6
	3	36	15.5	2.4

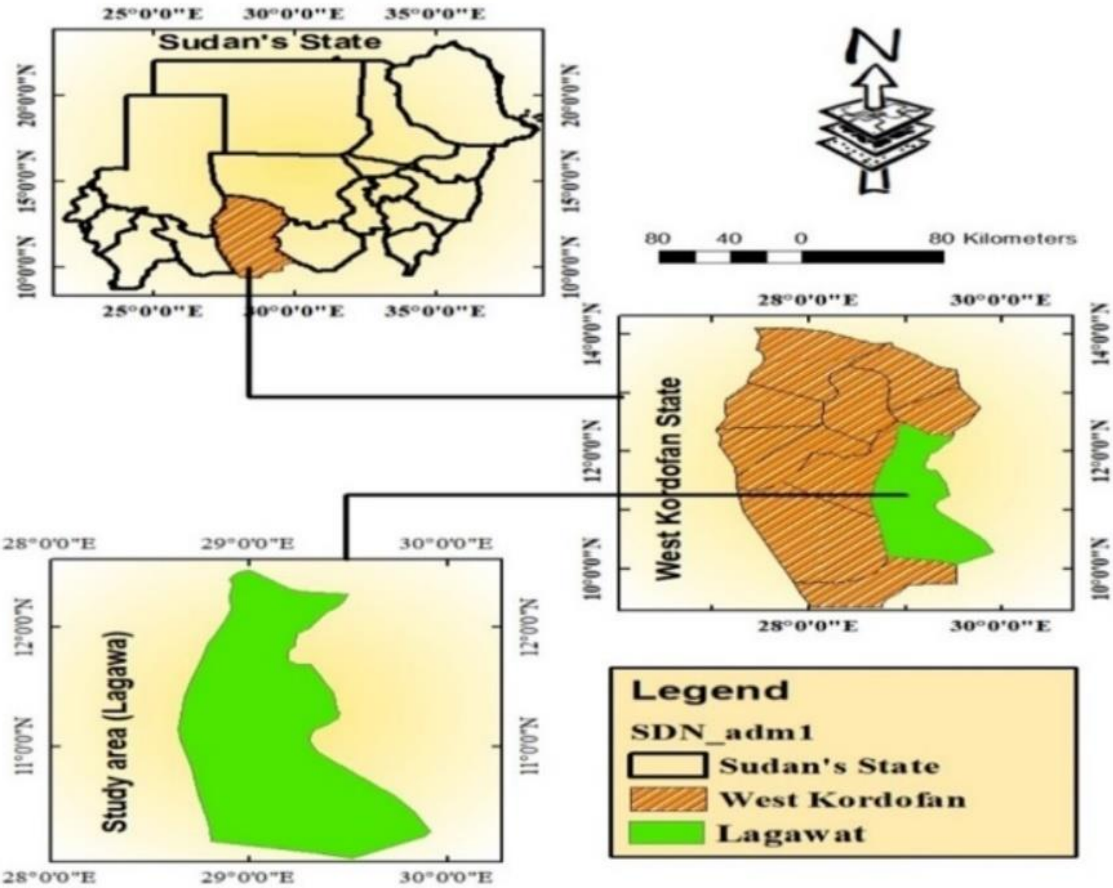

Figure 1. The study area

2.2 Methods

2.2.1 Sample collection and preparation

The trees were felled with a chainsaw and three 50-cm long sample logs were removed at 10, 50, and 90% along the bole length. The logs were sawn to 4 cm thick boards through the pith to the bark. Test specimens for the physical and mechanical properties were selected from wood around the pith, heartwood, and sapwood to represent innerwood, middlewood, and outerwood for each sampled log. Three replicates of test specimens were selected from each group (innerwood, middlewood, and outerwood). Other 20x20x30 mm specimens were taken from either end of all specimens prepared and used for mechanical testing to determine wood basic density based on oven-dry weight (Wo) per unit green volume (V_g) (ISO 3131 1975). The basic density of wood (BD g/cm^3) was calculated using the formula:

$$\mathrm{BD} = Wo/\mathrm{Vg} \tag{1}$$

The mechanical properties specimens were air-dried indoors to constant weight. The size of test specimens was 20x20x300 mm for MOR and MOE (ISO 3349 1975), 20x20x60 mm for CS (ISO 3787 1975), and 20x20x20 mm for SS (ISO 3347 1975). A universal testing machine was used to determine the mechanical properties. The following formulas were used to calculate the MOR, MOE, CS and SS (N/mm^2):

$$\mathrm{MOR} = \frac{3}{2}\frac{\mathrm{pl}}{\mathrm{bd^2}} \tag{2}$$

Where:

p: load
l: Length of span
b: width
d: depth.

$$\mathrm{MOE} = \frac{\mathrm{pl^3}}{4\Delta \mathrm{bd^3}} \tag{3}$$

Where:

p: load, at the limit of proportionality
l: length of span
Δ': deflection, at the limit of proportionality
b: width
d: depth.

$$\mathrm{CS} = \mathrm{P/A} \tag{4}$$

$$\mathrm{SS} = \mathrm{P/A} \tag{5}$$

Where:

P: Maximum load
A: Cross-sectional area.

2.3 Statistical Analysis

The data was organized in Microsoft Excel sheets and analyzed using SAS statistical package (SAS 1990). Nested analysis of variance was conducted using PROC Nested to investigate the significance of the variation among sources and their variance components (not to estimate the means of the sources and the differences among them). Using PRPC CORR, the coefficients of correlation and regression were conducted to determine the relationship between mechanical properties and basic density. The significant correlation coefficients were classified as strong ($r \geq 70$), moderate ($r \geq 50 < 69$), and weak ($r \leq 49$). The tests were performed at the significant level of $P \leq 0.05$.

3 RESULTS AND DISCUSSION

3.1 Wood Basic Density (BD)

Table 2 presents the mean values of the basic density (BD) for the *S. birrea and A. leiocarpus* wood. The BD for all specimens (n=1620) of *S. birrea* varied from 0.35 to 0.79 g/cm^3, and the mean value was 0.52 g/cm^3. Basic density for *A. leiocarpus* (n=1620) varied from 0.68 to 1.28 g/cm^3 and the mean was 0.92 g/cm^3. This study's mean BD for *S. birrea* is higher when compared to some reported values (0.49 g/cm^3) in Sudan (Mahgoub 2001). On the contrary, the study value was lower than the value (0.64 g/cm^3) reported in Saudi Arabia (Nasroun 2005). Similarly, *A. leiocarpus* wood has the greater BD in comparison to the values 0.82 g/cm^3 found by Mahgoub (2001), 0.88 g/cm^3 found by Mohammed (1999), and 0.731 g/cm^3 found by Ogunwusi et al. (2013). However, the study value was lower than the values of 1.150 g/cm^3 found by Bello-Jimoh (2018). The basic density of wood is the oven dry weight of wood material per green unit volume. Hence, it directly reflects the dry weight of wood as contained in freshly felled wood (Barnett – Jeronimidis 2003). At the same MC, one cubic meter of *A. leiocarpus* green wood is heavier than an equal volume of *S. birrea*. Based on the average BD, the oven-dry weight of one cubic meter of *S. birrea* green wood is estimated to be 520 kg and 940 kg for one cubic meter of *A. leiocarpus* wood. In some cases, it is of interest to estimate the weight of wood at a given MC if its dry weight is known. Then in both cases, the weight of one cubic meter will be multiplied by the actual wood volume to be transported. *Figure 2 and Figure 3* show the mean basic density at the examined vertical (10, 50, and 90%) and horizontal positions (innerwood, middlewood and outerwood).

Table 2. Mean value and descriptive statistic for basic density of wood (g/cm^3) of S. birrea and A. leiocarpus trees. (Min): Minimum; (Max): Maximum; (Std dev): Standard deviation; (CV): Coefficient of variation

Species	Min	Mean	Max	Std dev	CV%
S. birrea	0.35	0.52	0.79	0.06	11.53
A. leiocarpus	0.68	0.92	1.28	0.08	8.69

Results of the variance analysis of the nested random effects (*Table 3*) show that trees and vertical positions within trees were not significant sources of variation in basic density for *S. birrea* (p= 0.96 and p= 0.62, respectively). Nevertheless, horizontal positions within vertical positions were a significant (p= 0.0001) source of variation, although they contributed only 7.22% of the total variation. The percentage of the error variance component (92.77%) reveals that most of the variation in basic density was unexplained by the studied factors. Similar results were found for the basic density of *A. leiocarpus* in this study (*Table 3*). Trees and vertical position did not significantly influence basic density (p= 0.2 and p= 0.07, respectively). Rather, horizontal position was a significant source of variation (p= 0.0001), contributing 25.74% of the total variation. The unexplained variation amounted to 54.93%. The observed variation in wood density among the horizontal positions (from innerwood to outerwood) for both species may be due to the increasing age of cambium (Chowdhury et al. 2009, Izekor et al. 2010).

These results agree with previous research findings that a horizontal position was a significant source of variation in the basic density for hardwood species such as *A. leiocarpus, Eucalyptus grandis* and *Eucalyptus camaldulensis* (Sadiku 2018, Wessels et al. 2016). Similarly, results agree with reports for softwood species such as *Juniperus polycarpos* (Kiaei et al. 2015) and *Pinus kesiya* (Missanjo – Matsumura 2016). However, the results are not in line with previous research findings that vertical positions within trees were a significant source of variation in hardwoods; for instance, within *Acacia nilotica* (Ahmed 1998); *Tectona grandis* (Izkor et al. 2010); *Corylus colurna* (Zeidler 2012); *Acacia saligna*, (Mmolotsi et al. 2013); *Balanites aegytica* (Awad 2015), and *Albizzia julibrissin* (Kiaei - Farsi 2016).

Table 3. Nested random effects analysis of variance for basic density of S. birrea and A. leiocarpus wood. (***): P < 0.0001; (**): P < 0.001; (*): P < 0.05; (ns): not significant; (TR): tree; (VP): vertical position; (HP): horizontal position; (V comp): variable component

Variation sources	BD of *S. birrea*	BD of *A. leiocarpus*
TR	ns	ns
V comp%	0.00	0.00
VP(TR)	ns	ns
V comp%	0.00	0.00
HP(VP)	***	***
V comp%	7.22	25.74

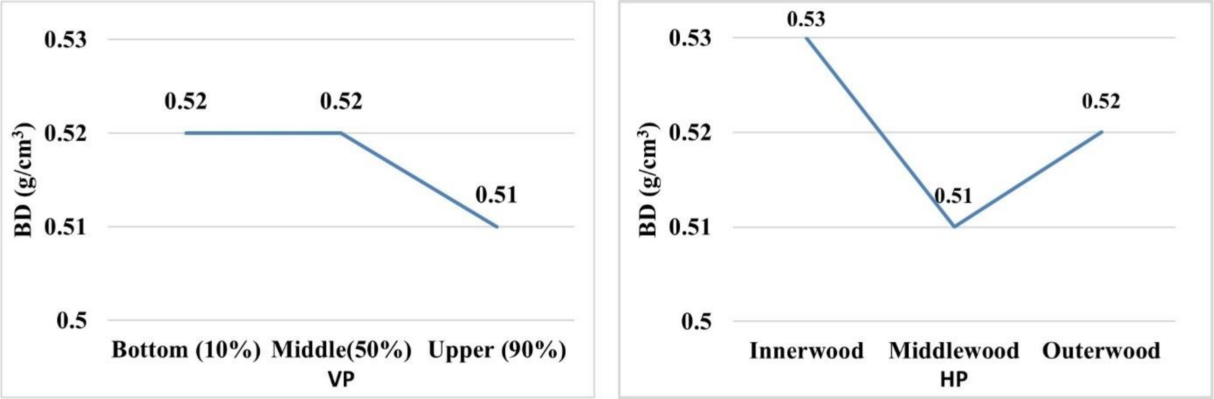

Figure 2. Showing the basic density within vertical and horizontal positions for S. birrea. (BD): basic density; (VP): vertical positions; (HP): horizontal positions

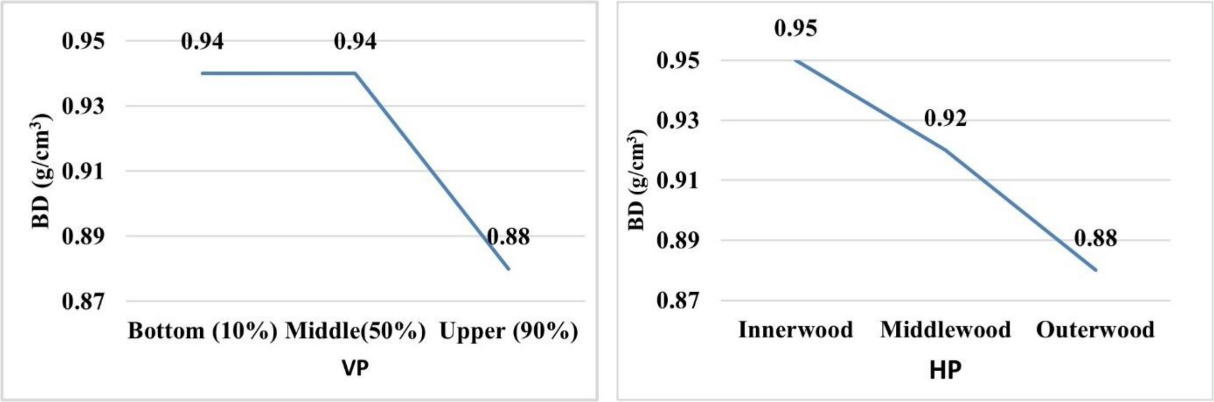

Figure 3. Showing the basic density within vertical and horizontal positions for A. leiocarpus. (BD): basic density; (VP): vertical positions; (HP): horizontal positions

3.2 Mechanical properties

Tables 4 and 5 present the mean values with standard deviation for the mechanical properties of *S. birrea* and *A. leiocarpus* wood. An analysis of variance of the nested random effects for mechanical properties shows that vertical positions (VP) were not a significant source of variation in the traits, except for MOR and MOE of *S. birrea (Table 6)*. The same can be said for MOE and CS of *A. leiocarpus (Table 7)*. However, the horizontal positions (HP) were a significant source of variation for both species in all traits. There are similar trends in mechanical properties among VP within trees of *Blanites aegyptiaca* (Awad 2015) and *Acacia melanoxylon* (Machado et al. 2014). The variations in mechanical properties among HP are probably due to several factors such as the density variability of the timber, cell arrangement and grain angle, and the microfibril angle within the cell wall (Panshin – de Zeeuw 1980). *Figures 4 and 5* show the mean mechanical properties at the examined VP (10, 50, and 90%) and HP (innerwood, middlewood, and outerwood).

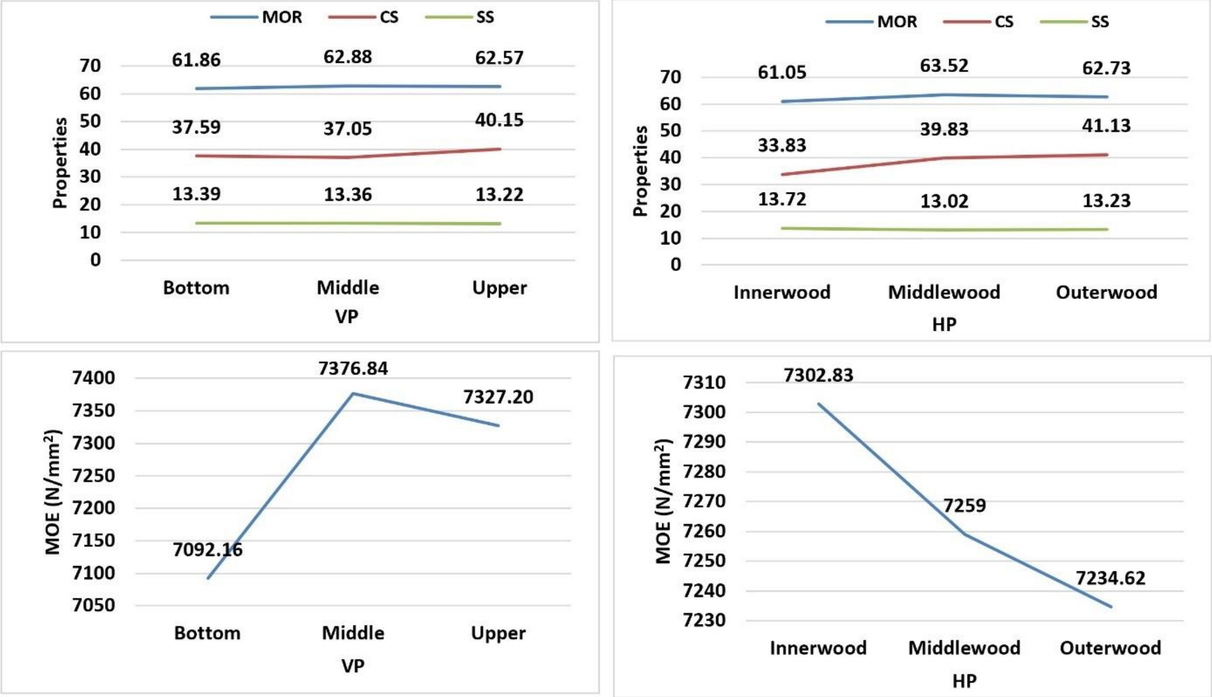

Figure 4. Showing the mechanical properties (N/mm^2) within VP and HP for S. birrea. (VP): vertical positions; (HP): horizontal positions; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain

Figure 5. Showing the mechanical properties(N/mm^2) within VP and HP for A. leiocarpus. (VP): vertical positions; (HP): horizontal positions; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain

Table 4. Mean values and simple statistics of mechanical properties in (Nmm^2) of S. birrea. (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain

Variable	Min	Mean	Max	Std. dev	CV%
MOR	37.13	62.43	96.03	10	16.02
MOE	2884.41	7265.4	10935.7	1381.87	19.02
CS	12.37	38.26	51.39	6.87	17.96
SS	4.86	13.32	19.26	3.09	23.20

Table 5. Mean values and simple statistic of mechanical properties in (Nmm^2) of A. leiocarpus. (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain.

Variable	Min	Mean	Max	Std. dev	CV %
MOR	41.12	96.97	146.01	18.45	19.03
MOE	4958	12577	23553	3434	27.30
CS	30.55	45.77	68.45	6.85	14.96
SS	5.60	16.64	27.94	4.10	24.09

Table 6. Nested Random Effects Analysis of Variance for basic density and mechanical properties of S. birrea wood. (***): P < 0.0001; (**): P < 0.001; (*): P < 0.05; (ns): not significant; (TR): tree; (VP): vertical position; (HP): horizontal position; (V comp): variable component.

Variation sources	MOR	MOE	CS	SS
TR	***	***	ns	ns
V comp%	11.08	16.15	0.00	0.00
VP(TR)	ns	ns	ns	ns
V comp%	0.00	0.00	0.00	0.00
HP(VP)	***	**	***	***
V comp%	12.79	13.09	48.30	21.76

Table 7. Nested Random Effects Analysis of Variance for basic density and mechanical properties of A. leiocarpus wood. (***): P < 0.0001; (**): P < 0.001; (*): P < 0.05; (ns): not significant; (TR): tree; (VP): vertical position; (HP): horizontal position; (V comp): variable component.

Variation sources	MOR	MOE	CS	SS
TR	***	Ns	ns	*
V comp%	20.07	0.00	0.00	15.01
VP(TR)	ns	***	ns	ns
V comp%	0.00	17.44	0.00	0.00
HP(VP)	*	***	***	***
V comp	6.03	8.79	18.57	13.53

3.3 Relationships between mechanical properties and basic density

The results of Pearson correlation analysis of *S. birrea* reveal no significant correlation (p= 0.11; r= 0.09 and p= 0.37; r= 0.05) for MOR and MOE with BD. There was a significant but weak positive correlation for CS (p= 0.0004; r= 0.21) and SS (p= 0.0001; r= 0.26). There are contrary results for the correlation of MOR and MOE with BD among other wood species; for example, the wood of *Acacia nilotica* (DafaAlla 1998) and *Balanites agyptiaca* (Awad 2015) in Sudan. Meanwhile, there were significant, weak positive correlations between all mechanical properties and BD of *A. leiocarpus (Table 8).*

The results of the correlation of mechanical properties with BD for both species studied were low, which suggests that relying on only the densities of the species for utilization can be a disadvantage. This suggestion agrees with Machado et al. 2014. The trends found by this study were not in agreement with the general perception that wood density had been considered a good indicator of wood strength (Shmulsky – Jones 2011). Previous research found significant, positive correlation of mechanical properties with wood density in *Tectona grandis* (Izekor et al. 2010) and *Borassus aethiopum* (Asafu et al. 2013). However, their coefficients of correlation ranged between 0.85 to 0.90 %.

Regression coefficients for the significant and insignificant correlation were considered. The regression coefficients of determination (R^2) values ranged from 0.02 to 0. 25, indicating that a small proportion of the variations in mechanical properties were explained by basic density. Consequently, coefficients of determination were low and did not indicate a good fit for both species *Fig 6 and 7*. Based on the results, the basic density of wood *S. birrea* and *A. leiocarpus* is not optimal to estimate the mechanical properties of the wood.

Table 8. Correlation coefficients (and probabilities) for mechanical properties with BD and of S. birrea and A. leiocarpus. (BD): basic density; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain

Mechanical properties	BD of wood *S. birrea*	BD of wood *A. leiocarpus*
MOR	0.09 (0.11)	0.33 (0.0001)
MOE	0.05 (0.37)	0.28 (0.0001)
CS	0.21 (0.0004)	0.30 (0.0001)
SS	0.26 (0.0001)	0.24 (0.0001)

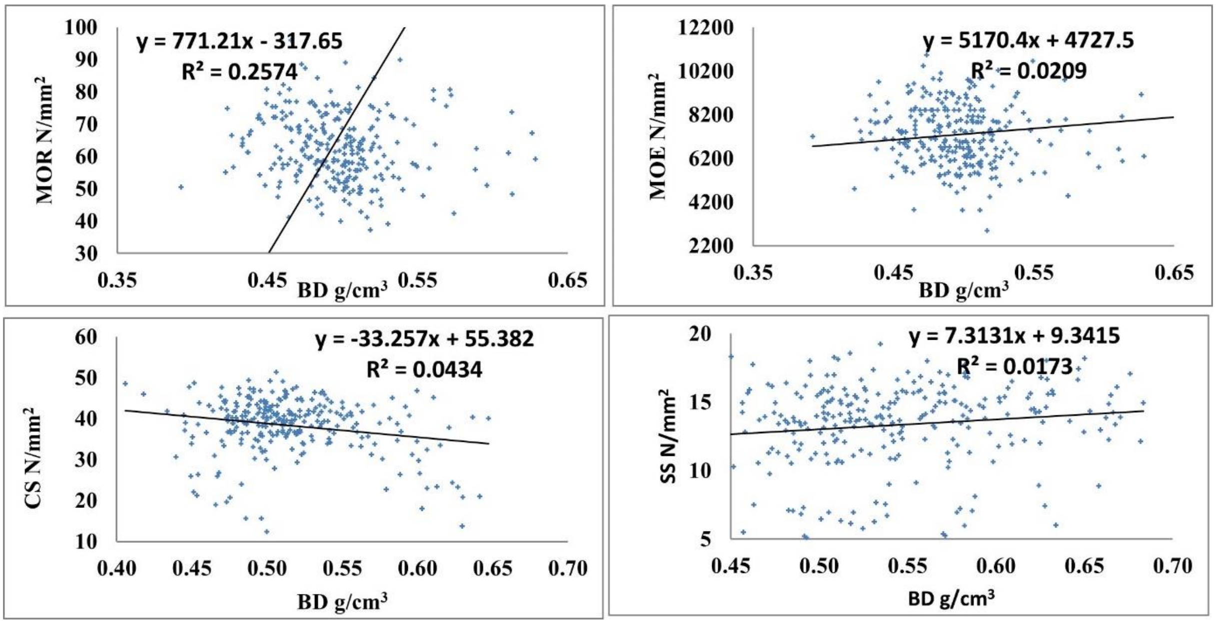

Figure 6. Relationships between mechanical properties and basic density of wood S. birrea tree. (BD): basic density; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain.

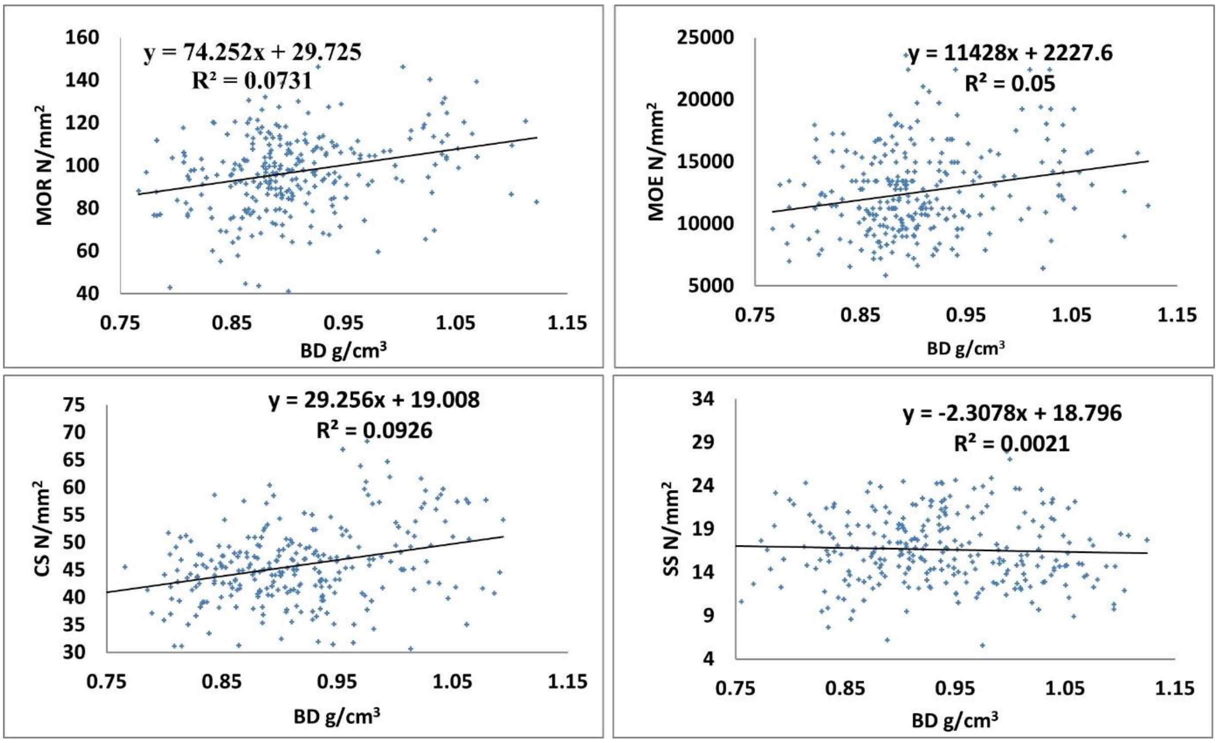

Figure 7. Relationships between mechanical properties and basic density of wood A. leiocarpus tree. (BD): basic density; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain.

5 CONCLUSIONS

The present study draws the following conclusions:

- Horizontal position within vertical position was a significant source of variation in basic density and selected mechanical properties for *S. birrea* and *A. leiocarpus*.
- Vertical position within trees was not a significant source of variation in basic density for *S. birrea* and *A. leiocarpus.*
- Vertical positions within trees were a significant source of variation in MOR and MOE for *S. birrea,* and in MOE and CS for *A. leiocarpus*.
- The correlations of BD with the selected mechanical properties are significant, weak for *A. leiocarpus* and only with CS and SS for *S. birrea*.

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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.

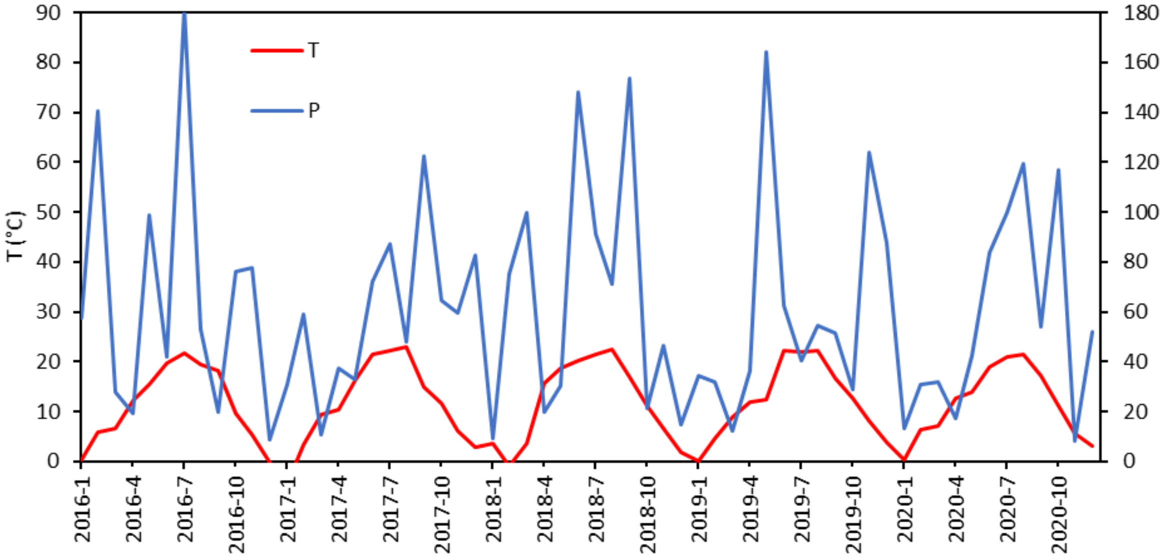

Figure 1. Monthly averages of air temperature (T) and sums of precipitation (P) measured at Sümeg between 2016 and 2020

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.

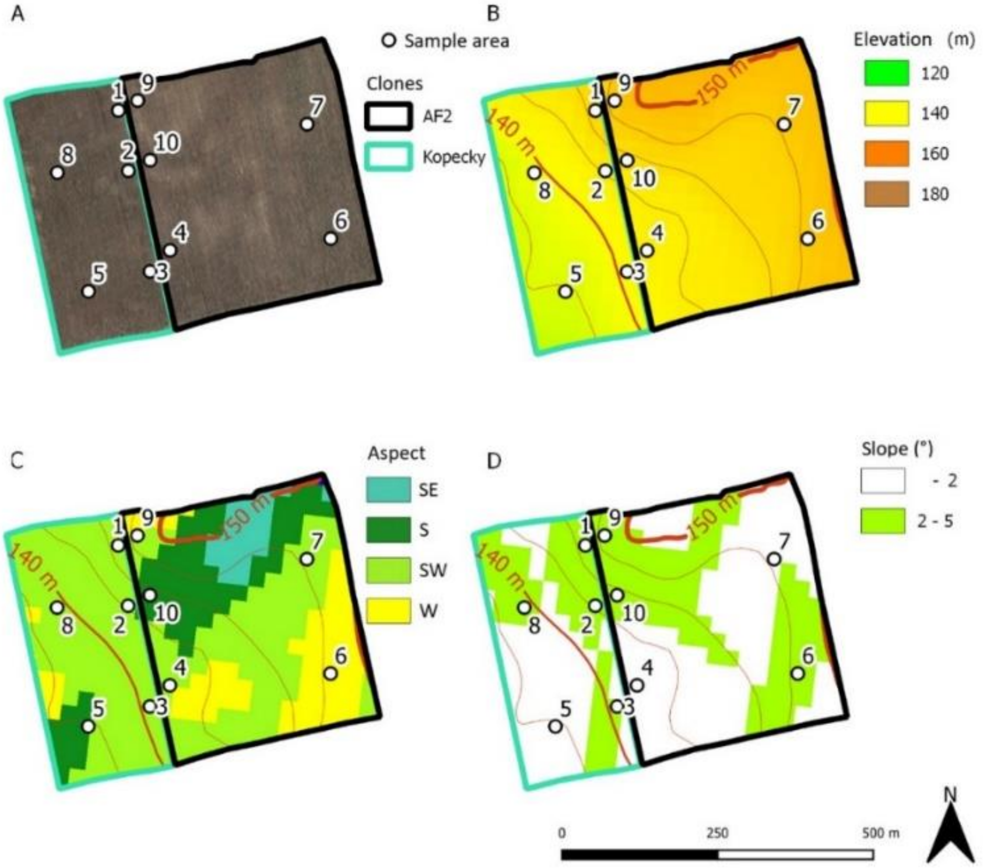

Figure 2. Maps of the research area (A – location of the samples areas, B – elevation map, C – Aspect map, and D – slope map)

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:	$h = a \times \ln(DBH) + b$				(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:	$TBM = a \times DBH^b$				(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.

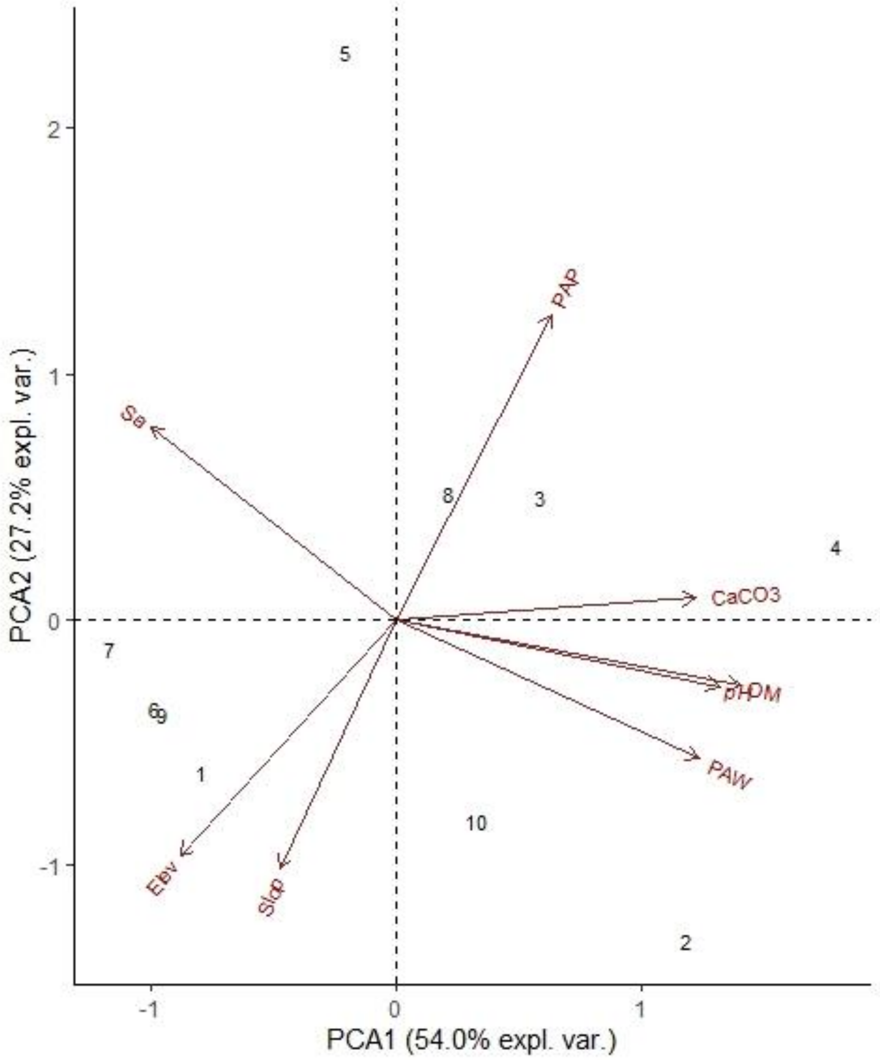

Figure 3. Ordination diagram of the PCA (Elev – elevation, Slope – slope, OM – organic matter, PAP – plant available phosphorus, Sa – sand fraction, and PAW – plant available water)

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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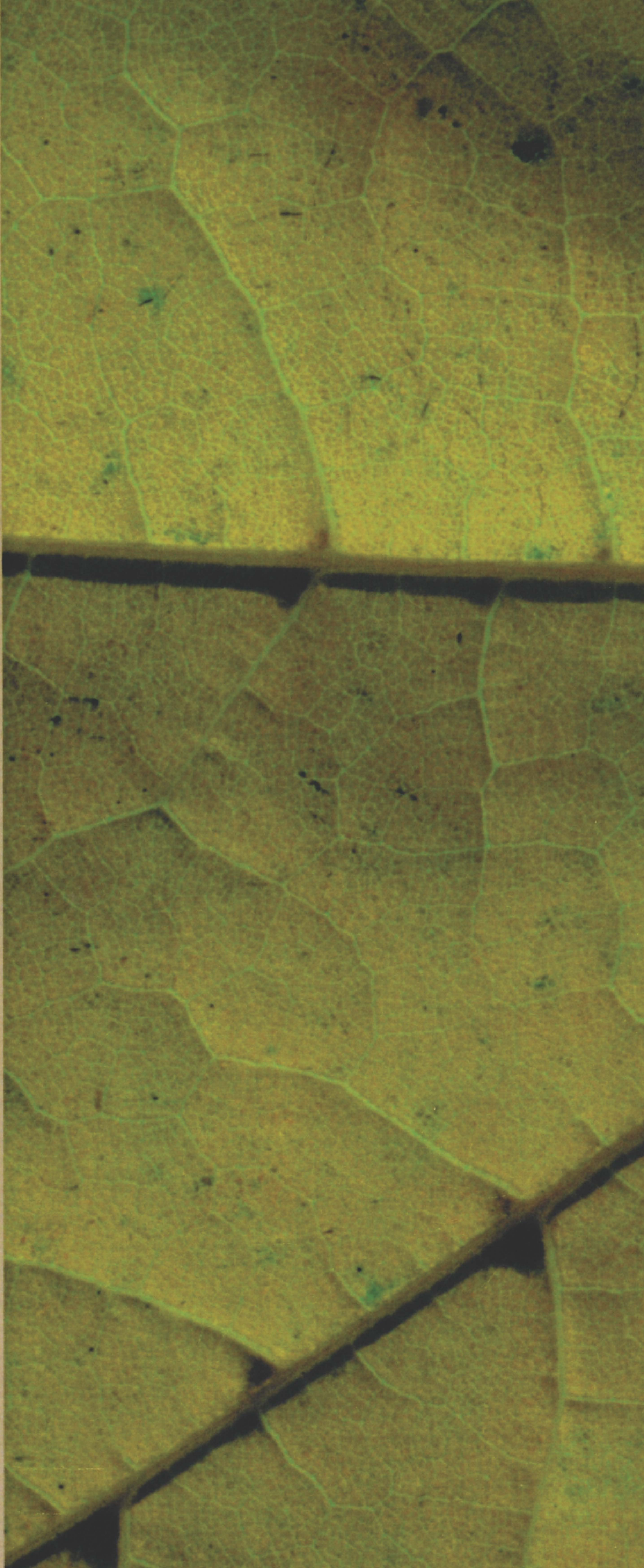

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