ACTA SILVATICA
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LIGNARIA
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ACTA SILVATICA & LIGNARIA HUNGARICA

AN INTERNATIONAL JOURNAL IN FOREST, WOOD AND ENVIRONMENTAL SCIENCES

VOLUME 18, NR. 1
VOLUME 18, NR. 2
2022

UNIVERSITY OF SOPRON PRESS

ACTA SILVATICA ET LIGNARIA HUNGARICA
AN INTERNATIONAL JOURNAL IN FOREST, WOOD AND ENVIRONMENTAL SCIENCES
issued by the Forestry Commission of the Hungarian Academy of Sciences

The journal is financially supported by the
Hungarian Academy of Sciences (HAS),
Faculty of Forestry, University of Sopron (FF-US),
Faculty of Wood Engineering and Creative Industries, University of Sopron (FWECI-US),
Forest Research Institute, University of Sopron (FRI-US),
Sopron Scientists' Society of the Hungarian Academy of Sciences (SSS).

HU ISSN 1786-691X (Print)
HU ISSN 1787-064X (Online)

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Information and electronic edition: https://aslh.nyme.hu

The journal is indexed in the CAB ABSTRACTS database of CAB International; by SCOPUS, Elsevier's Bibliographic Database and by EBSCOhost database.

Published by UNIVERSITY OF SOPRON PRESS,
BAJCSY-ZS. U. 4., H-9400 SOPRON, HUNGARY
Cover design by ANDREA KLAUSZ
Printed by LŐVÉR-PRINT KFT., SOPRON

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https://doi.org/10.37045/aslh-2022-0001 Acta Silv. Lign. Hung., Vol. 18, Nr. 1 (2022) 9–24

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	47º41'33.0"N, 17º02'06.0" E	47º41'32.4"N, 17º02'0.4.0"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

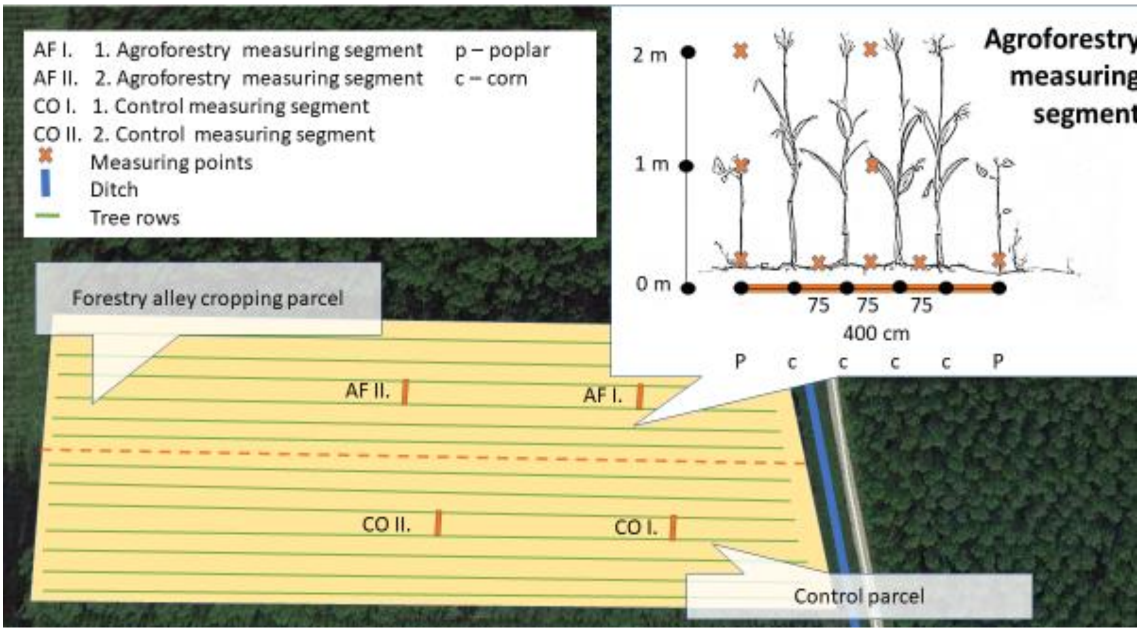

Figure 1. Experimental plot

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).

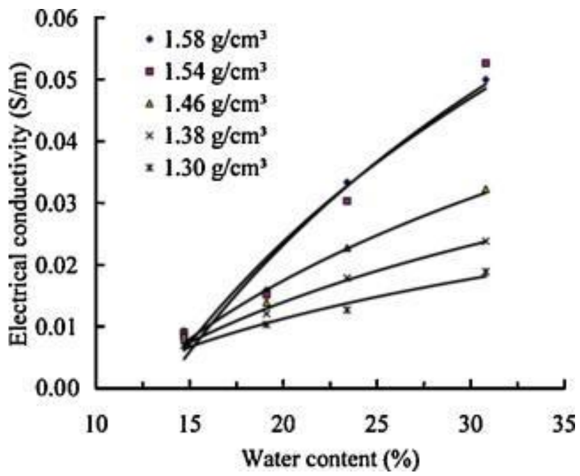

Figure 2. The relationship between electrical conductivity and water content of soil according to soil density (Bai et al. 2013)

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*).

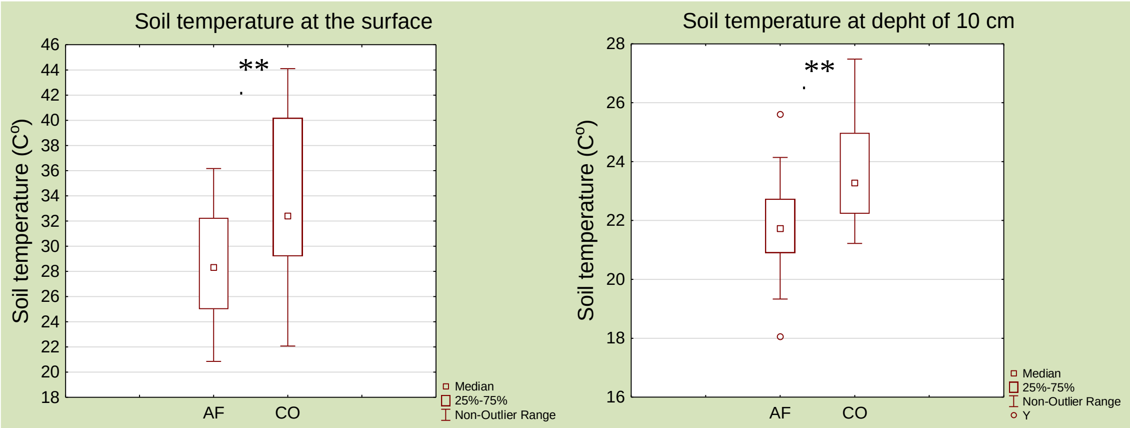

Figure 3. Soil temperature at the surface and depth of 10 cm in 2020 (AF - Average values from agroforestry measuring segment, CO - Average values from control measuring segment, n=200 observation, *significance level:**p≤0.01)*

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 ($F = 24.88$, $p \leq 0.01$; *Figure 3*). Soil surface temperature data for the agroforestry area provided more favorable values ($F = 14.94$, $p \leq 0.01$; 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 ($F = 11.61$, $p \leq 0.01$; *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.

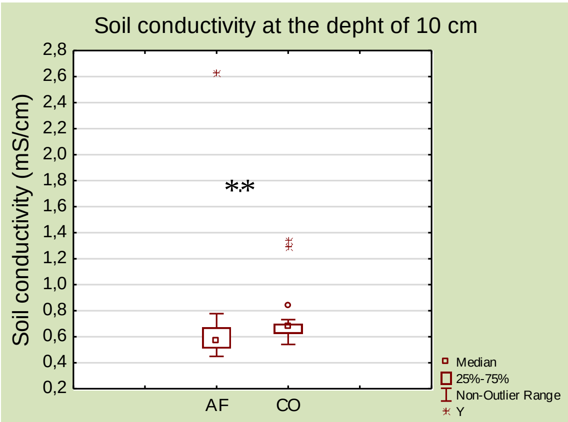

*Figure 4. Electrical conductivity at a depth of 10 cm in 2020 (AF - Average values from agroforestry are measuring segment, CO - Average values from control measuring segment, n=200, significance level:**p<0.01)*

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.

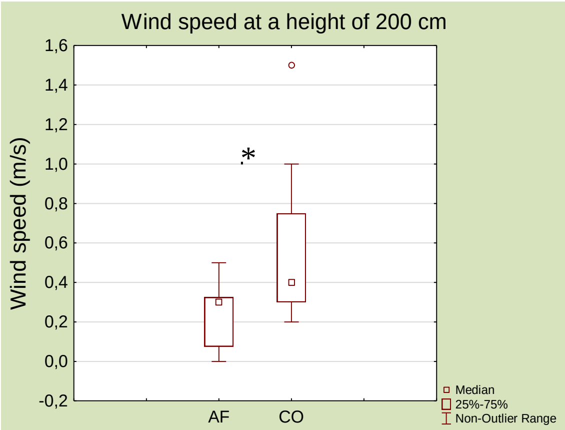

*Figure 5. Wind speed in 2020 (AF – Agroforestry system values, CO – Control system values, n=80, significance level:*p<0.05)*

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

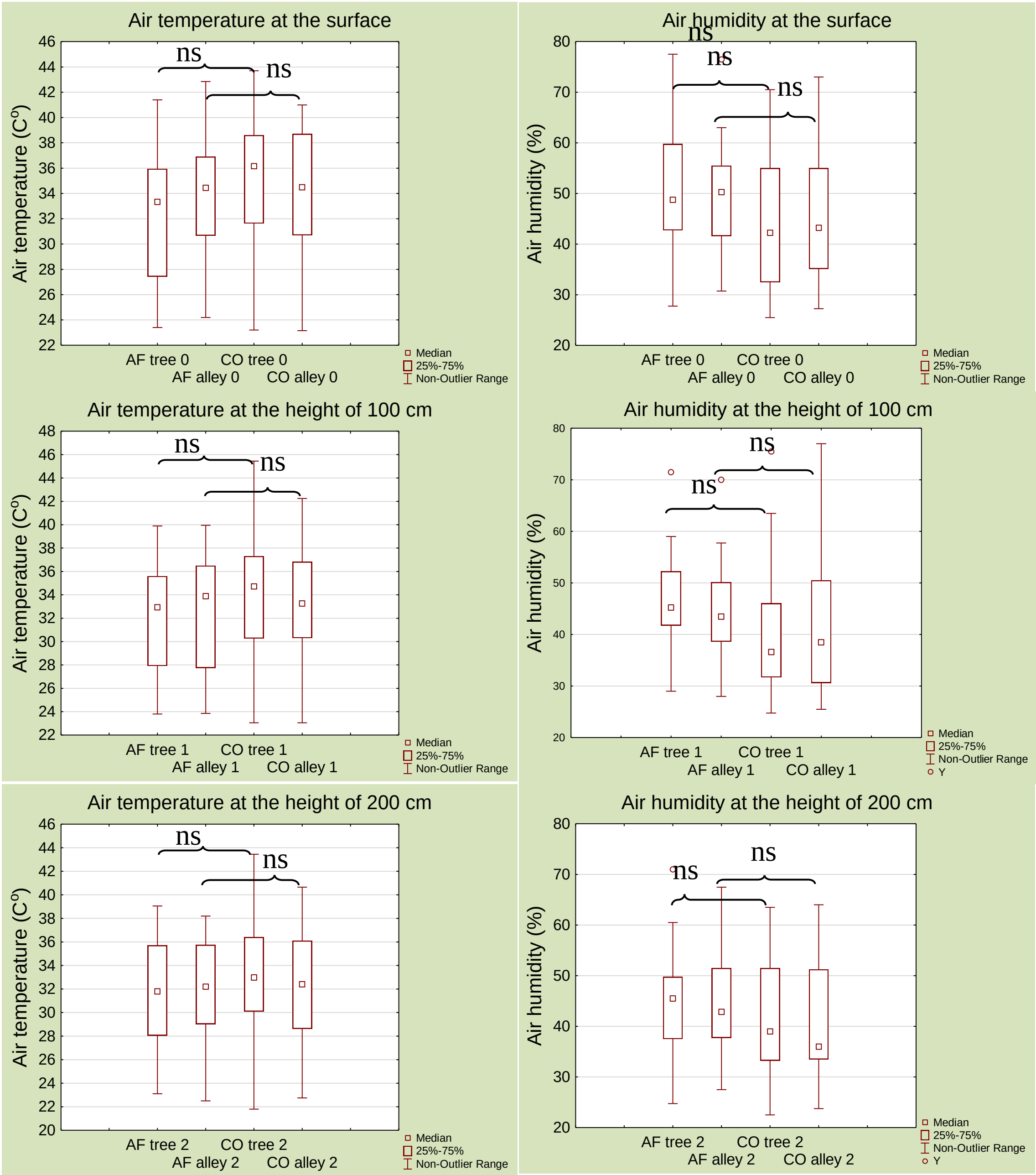

Figure 6. Air temperature and humidity values in 2020 (AF alley - Agroforestry segment values from alley, AF tree - Agroforestry segment values from tree row, CO alley - Control segment values from alley, CO tree - Control segment values from tree row, n=40, significance level: ns: non-significant)

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.

Acknowledgements: This article was completed within the frame of the EFOP-3.4.3-16-2016-00022 „Qualitas - development of higher education in Sopron, Szombathely and Tata" and GINOP-2.3.3-15-2016-00039" investigation of wood biomass cultivation conditions" projects.

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https://doi.org/10.37045/aslh-2022-0002 Acta Silv. Lign. Hung., Vol. 18, Nr. 1 (2022) 25–40

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).

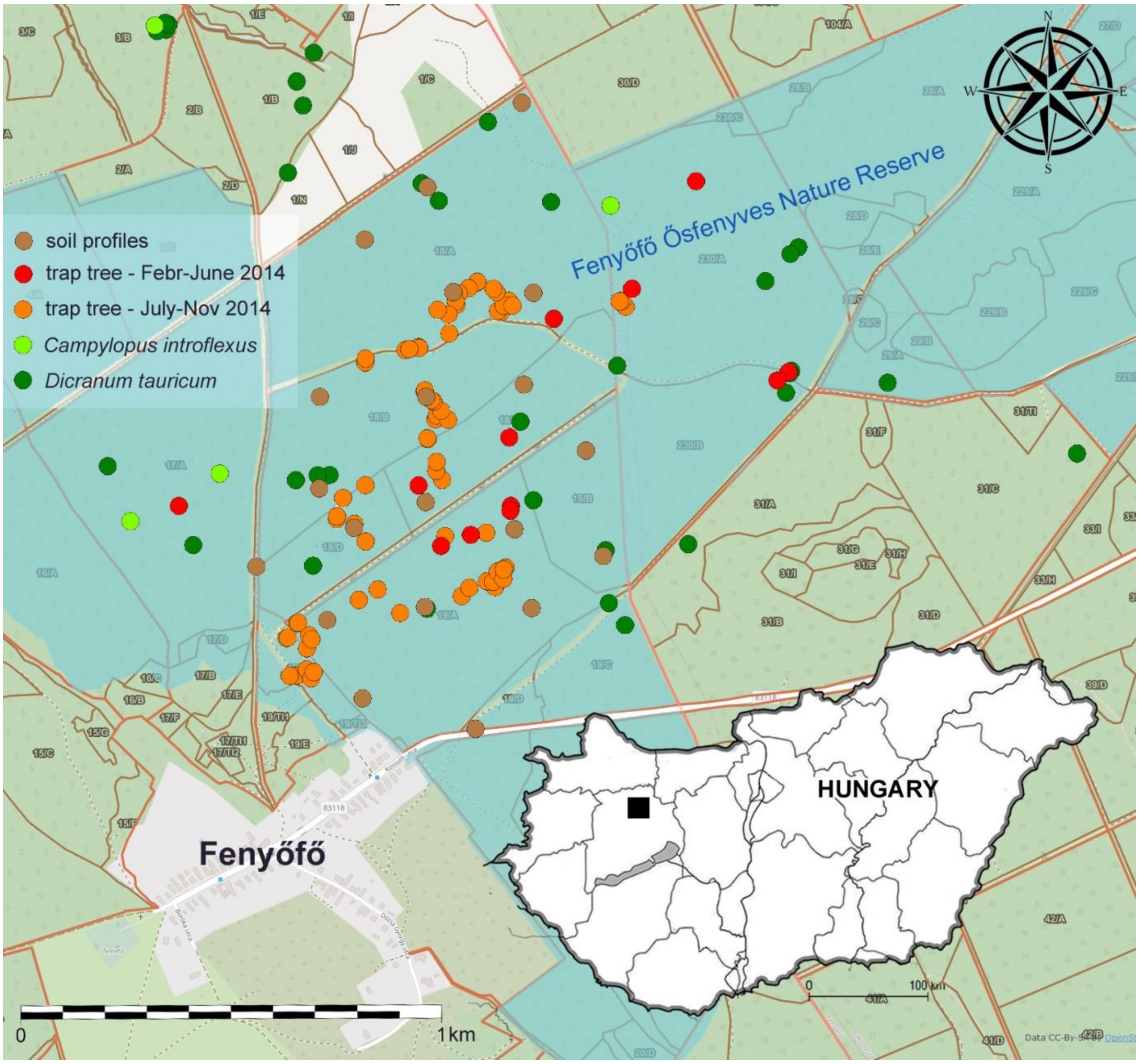

Figure 1. The location of the research site and the sampling points. (Numbers are showing the forest subcompartments)

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).

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

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:	$(6.75 \text{ x } 10^{-7})\ I^3 - (7.71 \text{ x } 10^{-5})\ I^2 + (1.792 \text{ x } 10^{-2})\ I + 0.49239$
I:	$\sum_{i=1}^{12} \left(\frac{\text{Tmean}}{5}\right)^{1.514}$

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).

$$REW = EW / EWm \qquad (2)$$
$$Is = \sum SWD / EWm \qquad (3)$$
$$SWD = EWm * 0.4 - EW \qquad (4)$$

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*).

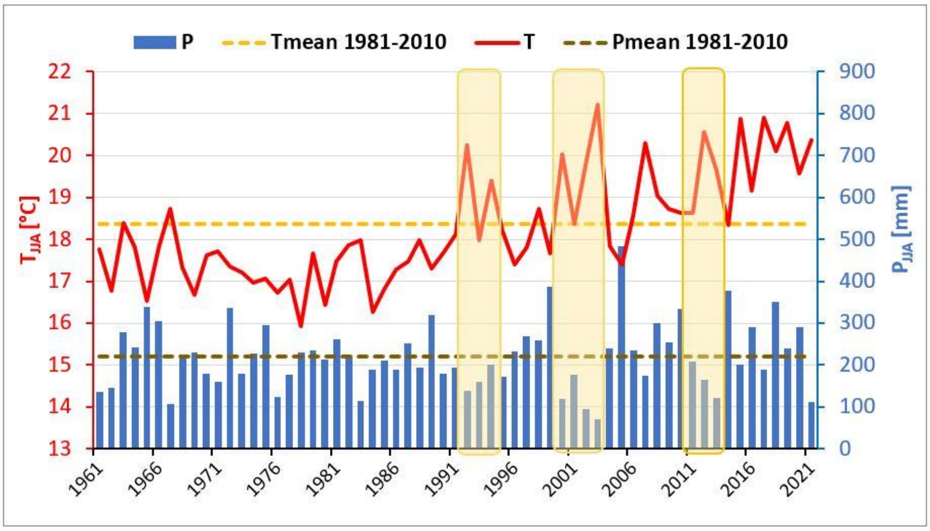

Figure 2. Mean summer temperature and precipitation sum for the period 1961–2021. Shaded areas indicate the consecutive drought periods.

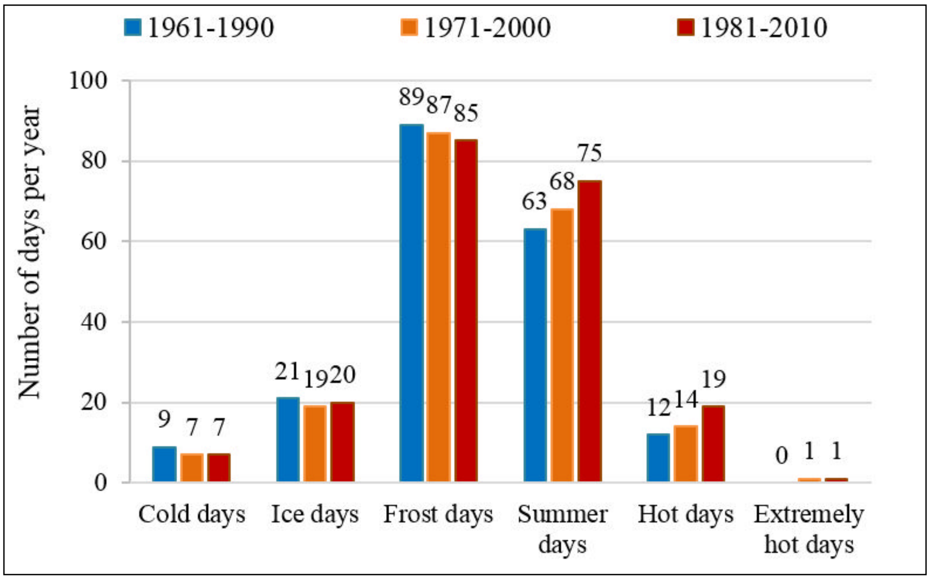

Figure 3. Total number of extreme low and high temperature in three different time periods (1961–1990; 1971–2000; 1981–2010)

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.

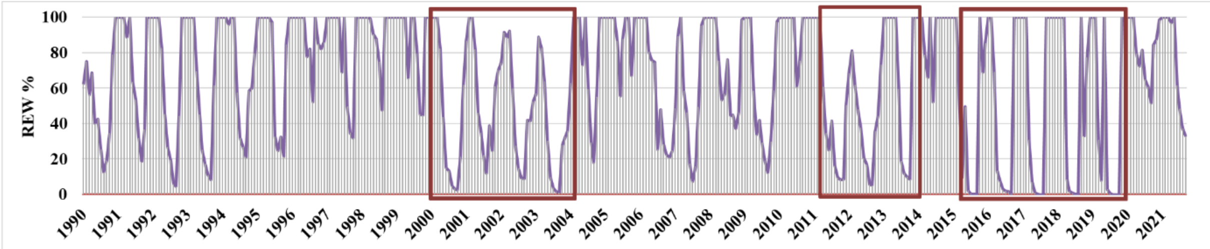

Figure 4. Relative water capacity based on Thornthwaite water balance model 1961–2021 (red frames highlighted the drought periods)

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*).

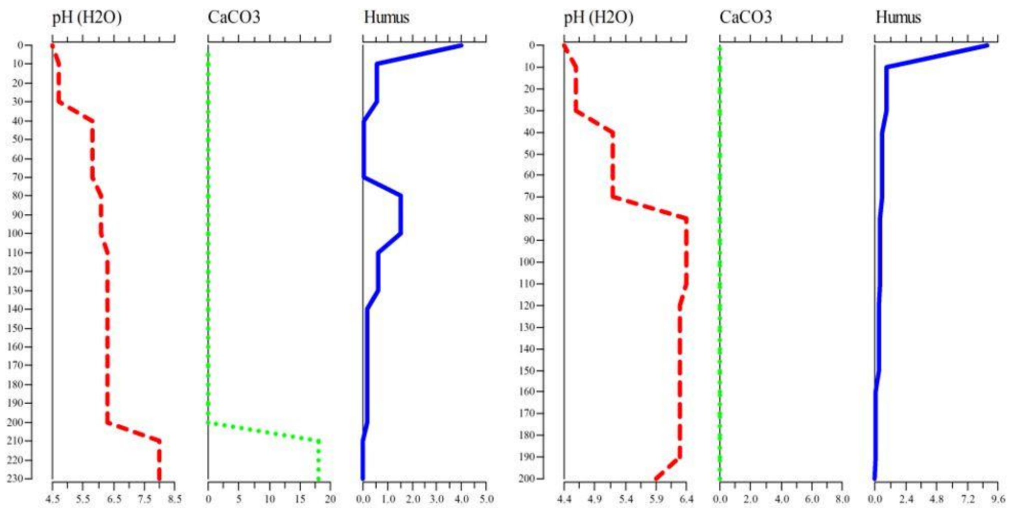

Figure 5. Distribution of soil pH_{H2O}, $CaCO_3$ content and Humus% in profile 5 (left) and in profile 15 (right).

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.

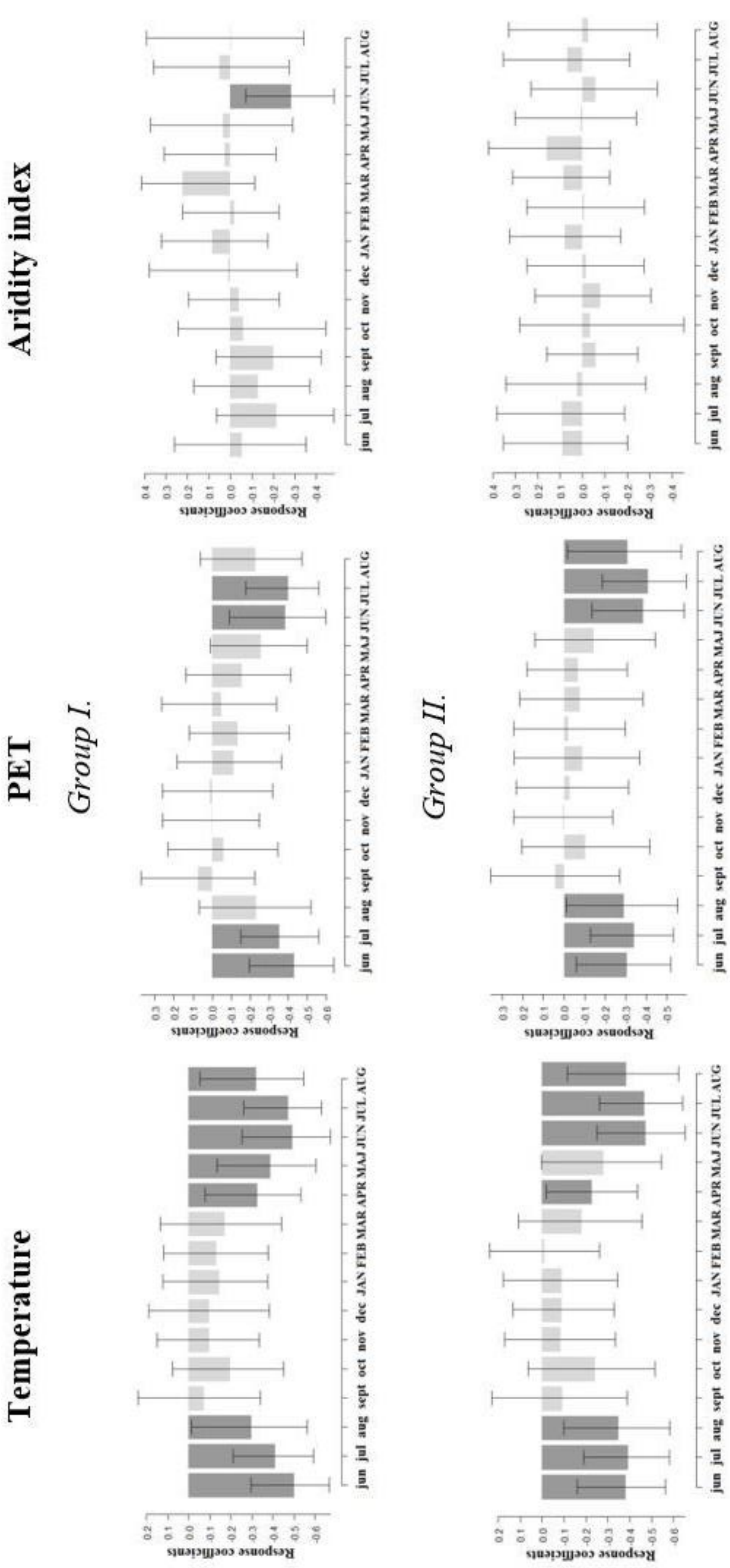

Figure 6. Results of Thornthwaite water balance model 1961–2021 was correlated with different climate parameters. Small letters representing the previous year and capital letters the year of growth. Light grey is the correlation values, where dark colour represents bootstrapped correlations significant 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.

Acknowledgements: This article was made in frame of the “EFOP-3.6.1-16-2016-00018 - Improving the role of research+development+innovation in the higher education through institutional developments assisting intelligent specialization in Sopron and Szombathely”. Borbála Gálos was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. The authors thank all of the co-workers for their support. Special thanks to the Bakonyerdő Ltd. for the cooperation.

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https://doi.org/10.37045/aslh-2022-0003 Acta Silv. Lign. Hung., Vol. 18, Nr. 1 (2022) 41–56

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 Mecomorn 750 SL	50% 5%	480 g/l glyphosate 750 g/l MCPA
3.	Medallon Premium Banvel 480 S	50% 5%	480 g/l glyphosate 480 g/l dicamba
4.	Medallon Premium Lontrel 300	50% 5%	480 g/l glyphosate 300 g/l clopyralid
5.	Medallon Premium Tomigan 250 EC	50% 5%	480 g/l glyphosate 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 Mezzo 20 WG	40% 1%	160 g/l 2.4 D + 320 g/l glyphosate 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.

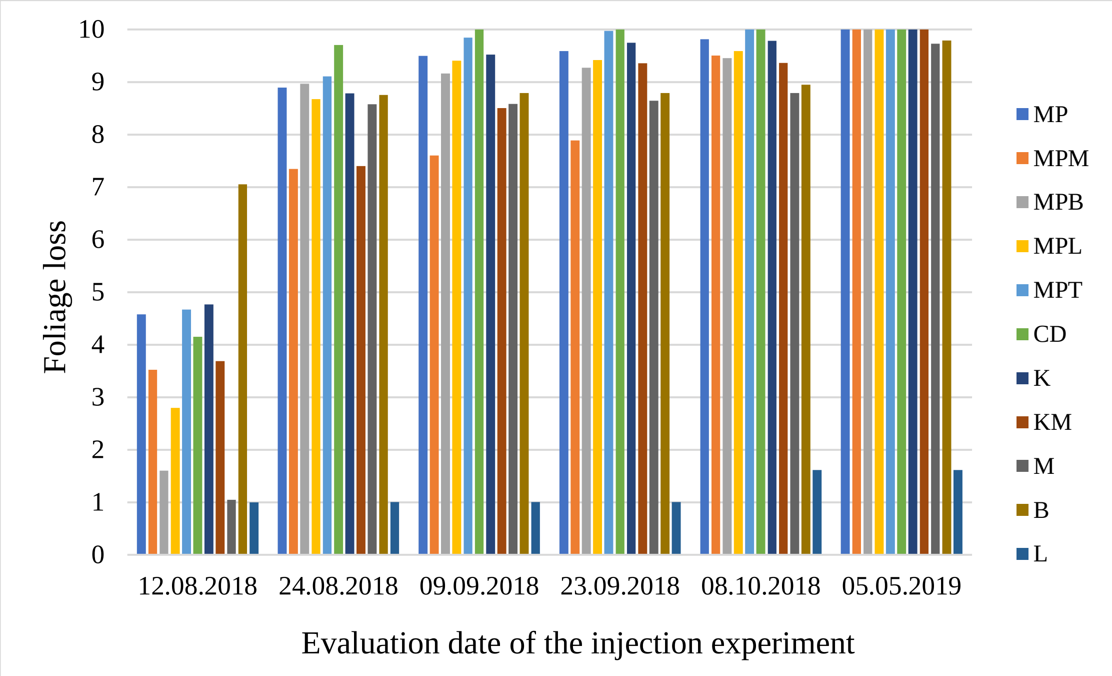

Figure 1. Effectiveness of formulations used in the trunk injection experiment conducted on July 25. MP: Medallon Premium, MPM: Medallon Premium - Mecomorn 750 SL, MPB: Medallon Premium - Banvel 480 S, MPL: Medallon Premium - Lontrel 300, MPT: Medallon Premium - Tomigan 250 EC, CD: Chikara Duo, K: Kyleo,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

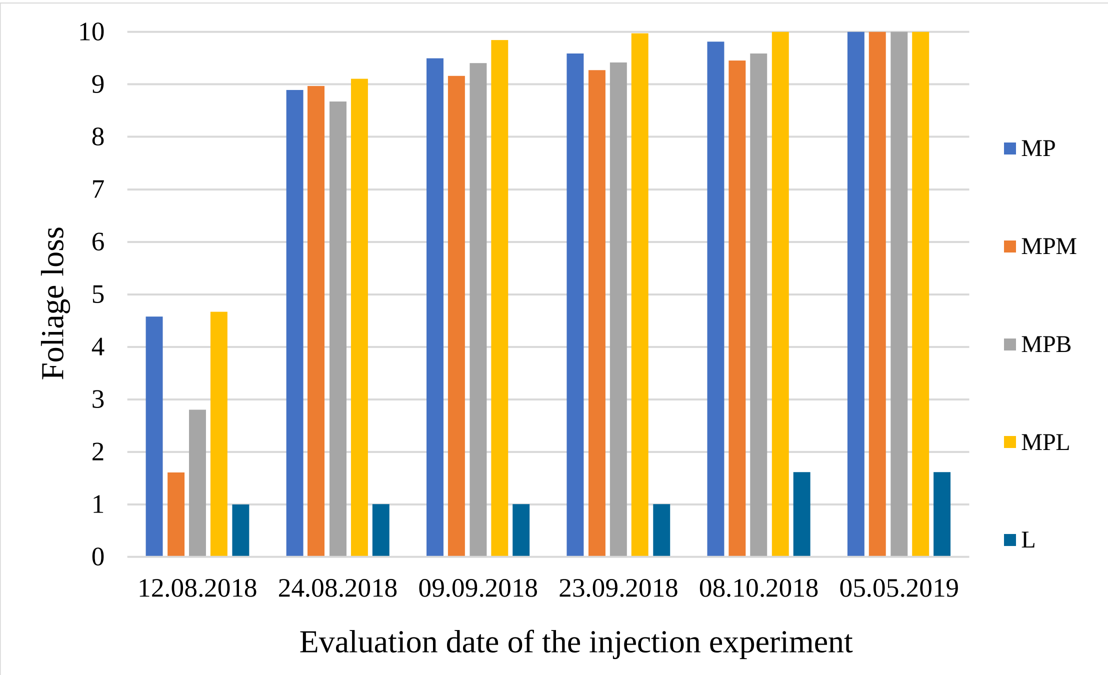

Figure 2. Effectiveness of the formulations used in the trunk injection experiment conducted on July 25 that did not stimulate sprouting. Abbreviations: see Figure 1.

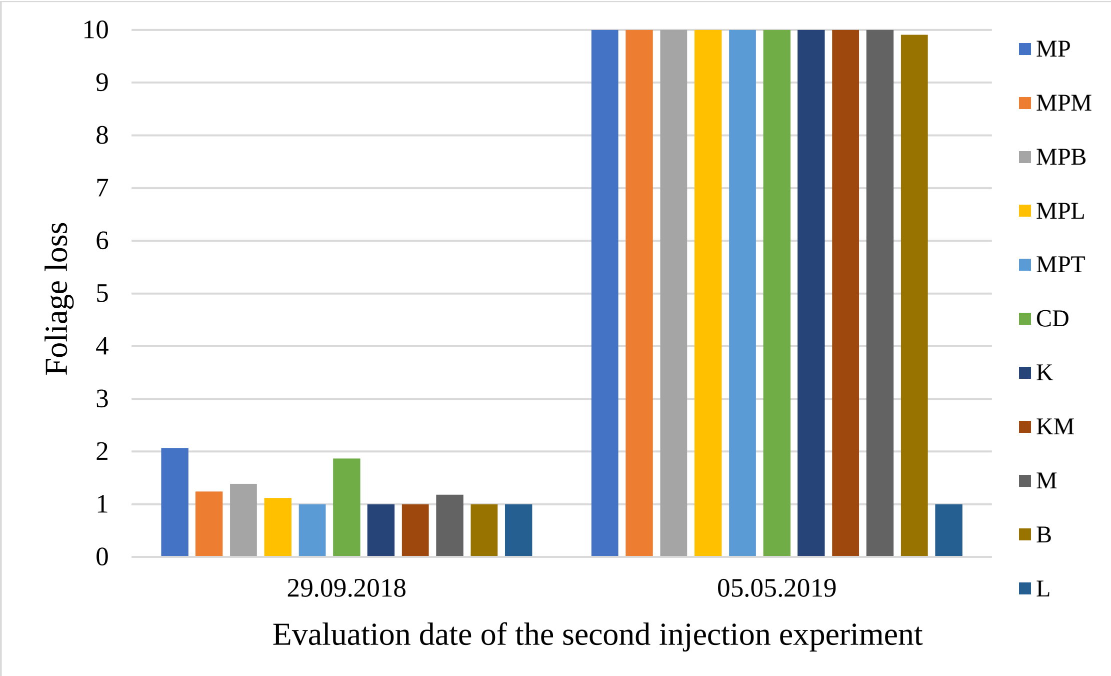

Figure 3. Effectiveness of formulations used in the trunk injection experiment conducted on September 15. Abbreviations: see Figure 1.

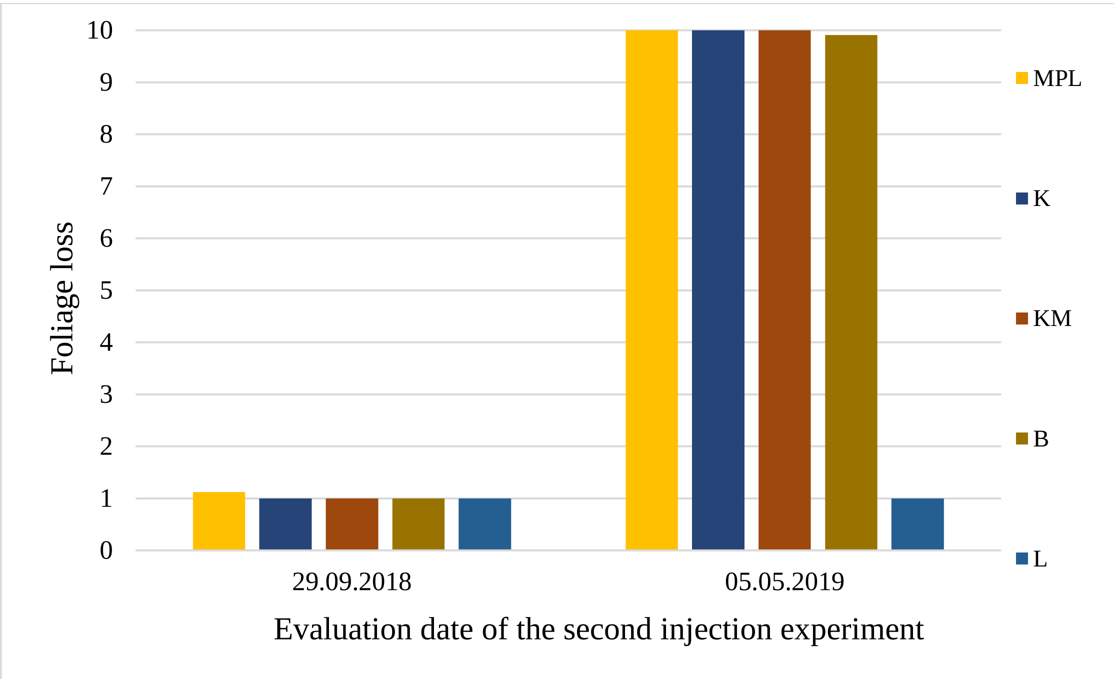

Figure 4. Effectiveness of the formulations used in the second trunk injection experiment conducted on September 15, that did not stimulate sprouting. Abbreviations: see Figure 1.

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.

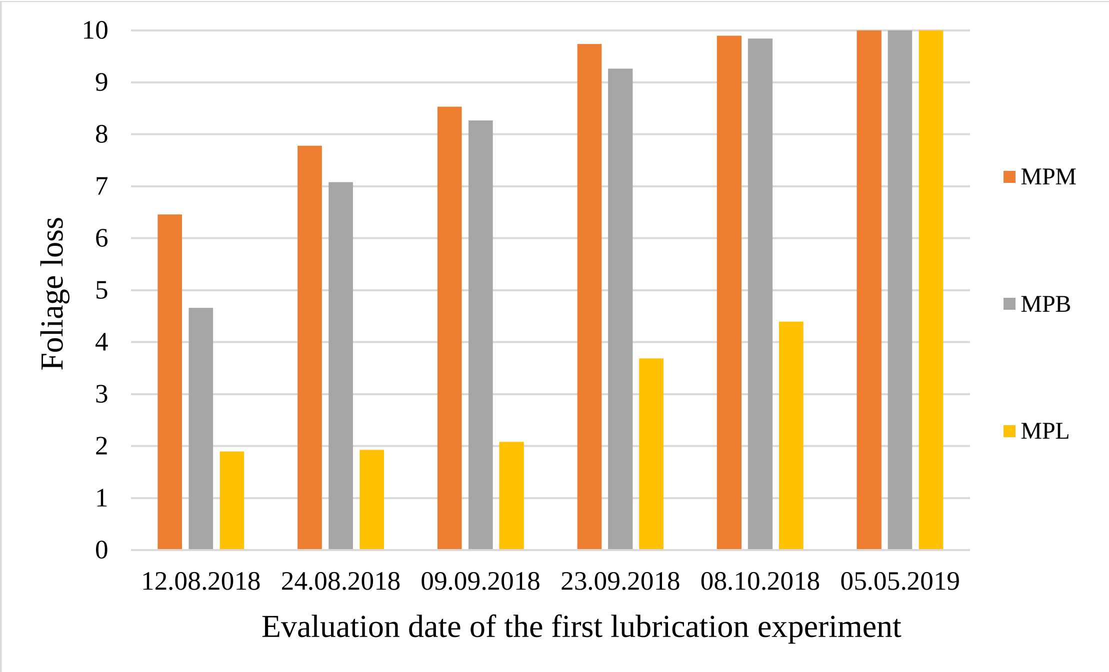

Figure 5. Effectiveness of formulations used in the bark treatment experiment conducted on July 25. Abbreviations: see Figure 1.

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

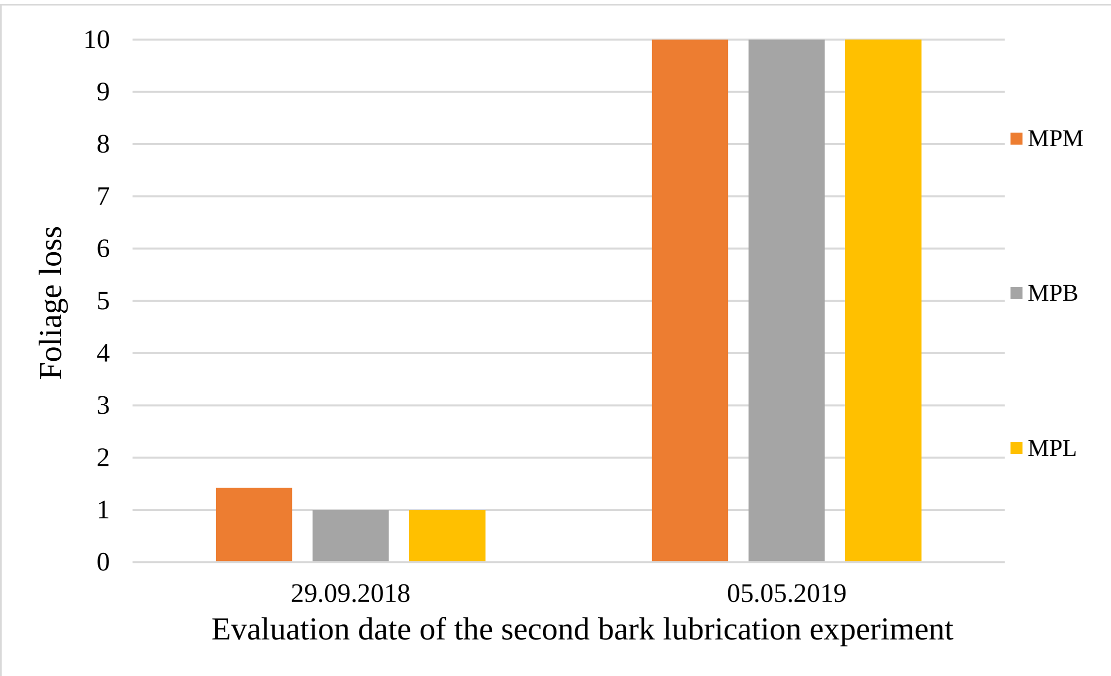

Figure 6. Effectiveness of formulation used in the bark treatment experiment conducted on September 15. Abbreviations: see *Figure 1.*

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.

Acknowledgements: We would like to thank István Hegede for his help in executing the experiments in the field. We would like to express our gratitude to all associates of Valkói Forestry of Pilisi Parkerdő Zrt. who permitted the experiment to take place and provided the necessary environment for the creation of the formulations.

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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)
	1	40	13	2.0
S. birrea	2	42	16	2.5
	3	47	17	3.5
	1	35	16	2.0
A. Leiocarpus	2	38	15	2.6
	3	36	15.5	2.4

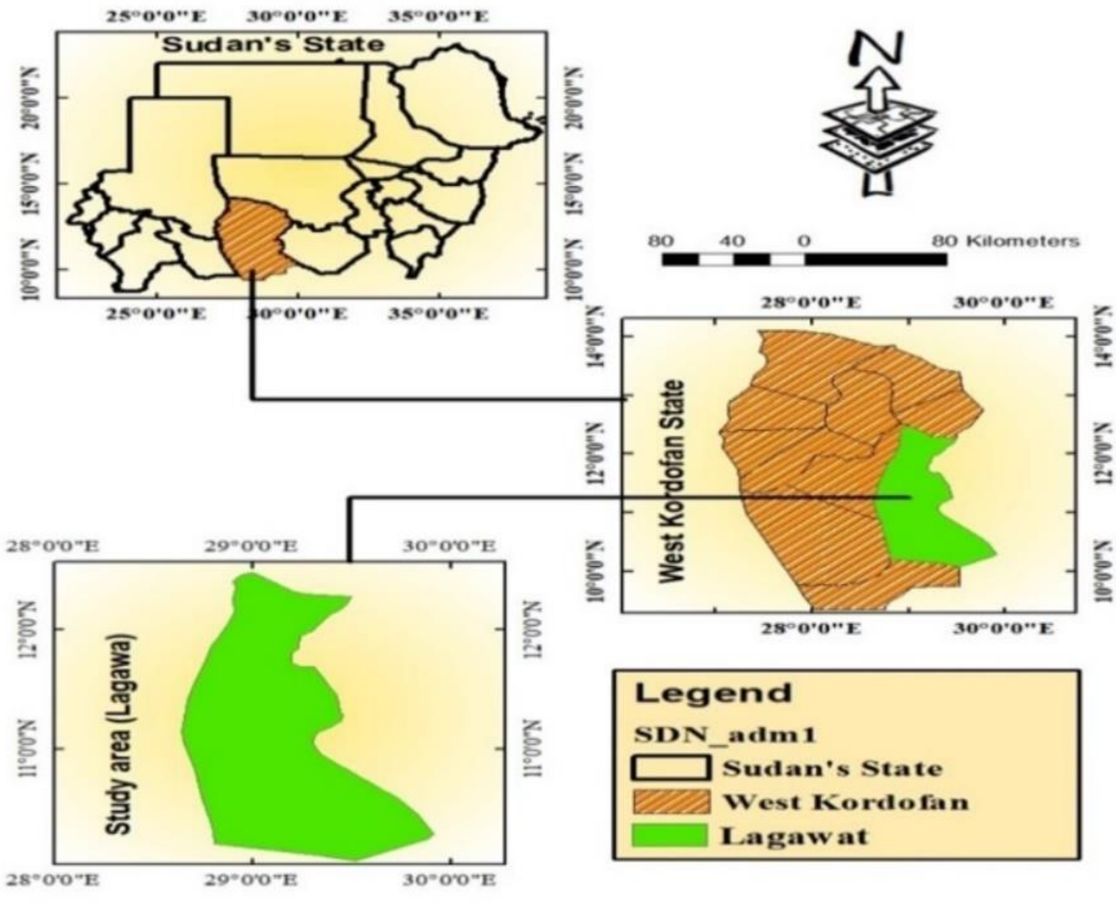

Figure 1. The study area

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 ≥ 70), moderate (r ≥ 50 < 69), and weak (r ≤ 49). The tests were performed at the significant level of P≤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

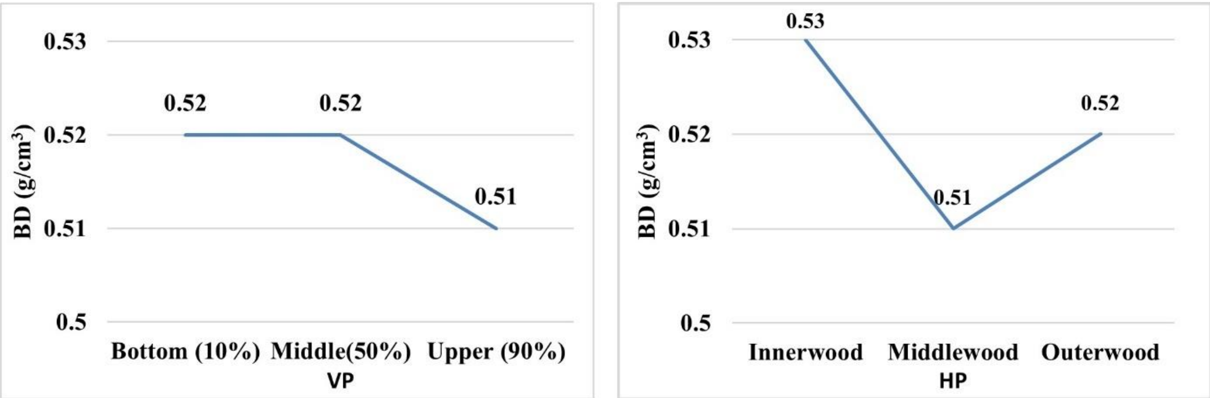

Figure 2. Showing the basic density within vertical and horizontal positions for S. birrea. (BD): basic density; (VP): vertical positions; (HP): horizontal positions

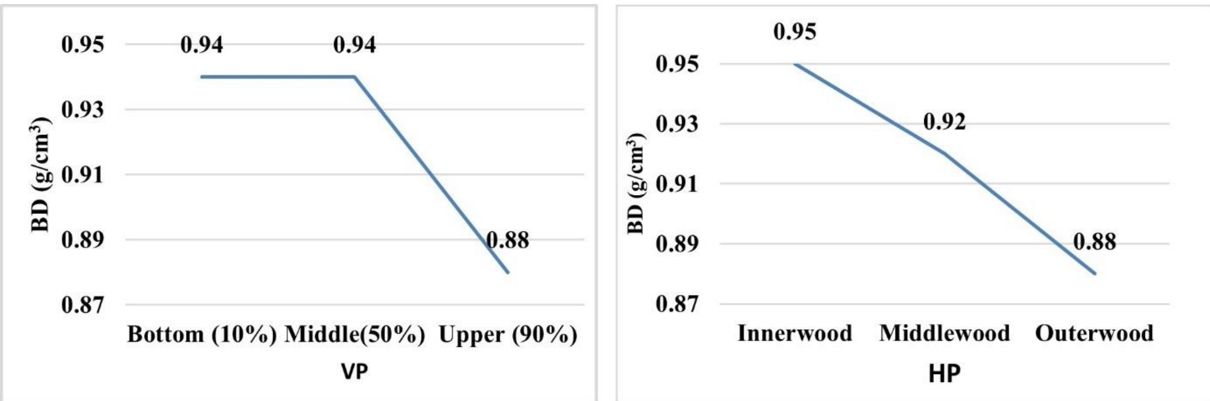

Figure 3. Showing the basic density within vertical and horizontal positions for A. leiocarpus. (BD): basic density; (VP): vertical positions; (HP): horizontal positions

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).

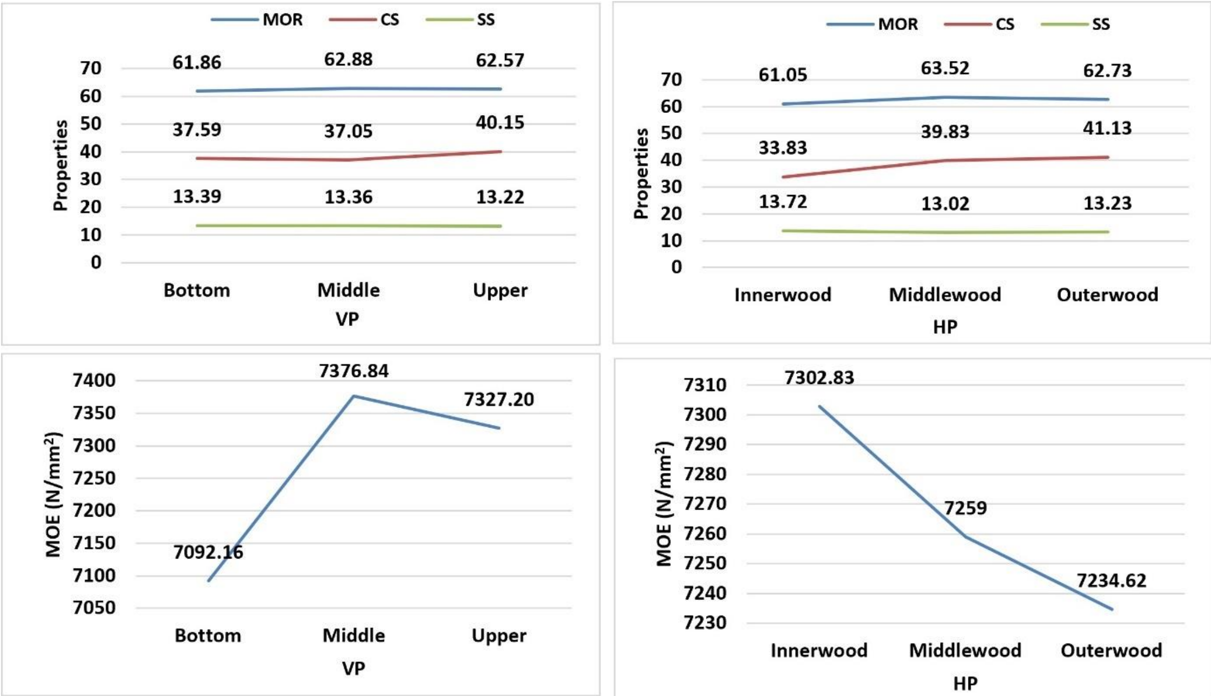

Figure 4. Showing the mechanical properties (N/mm^2) within VP and HP for S. birrea. (VP): vertical positions; (HP): horizontal positions; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain

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)

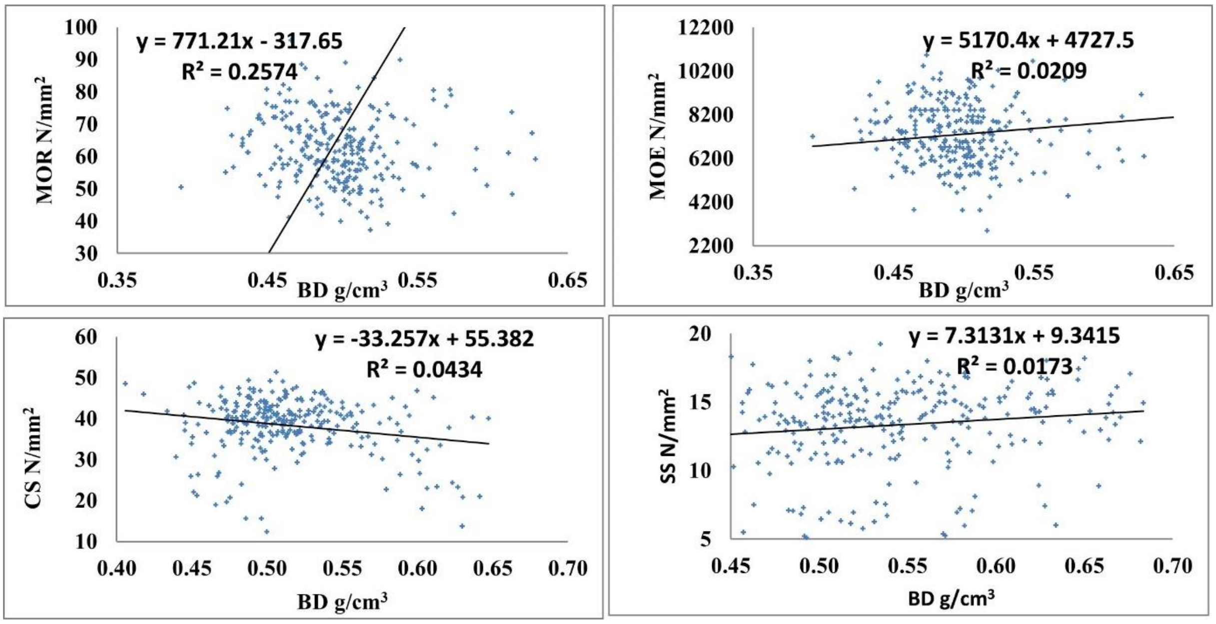

Figure 6. Relationships between mechanical properties and basic density of wood S. birrea tree. (BD): basic density; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain.

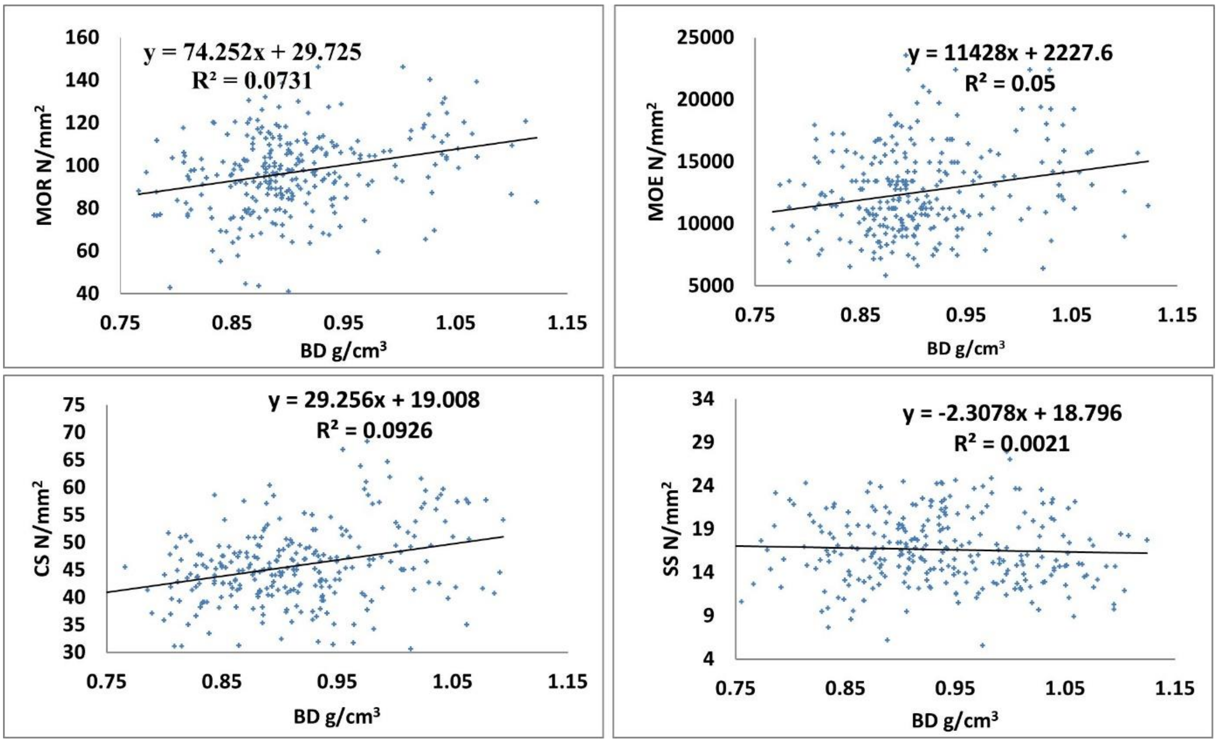

Figure 7. Relationships between mechanical properties and basic density of wood A. leiocarpus tree. (BD): basic density; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain.

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*.

Acknowledgements: We wish to thank the Ministry of Higher Education and Scientific Research in Sudan for partially funding this study. Thanks to Mr. Emad H. E. Yasin for preparing the map of the study area. Many thanks to Professor Bejó László for his comments to strengthen the article.

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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.

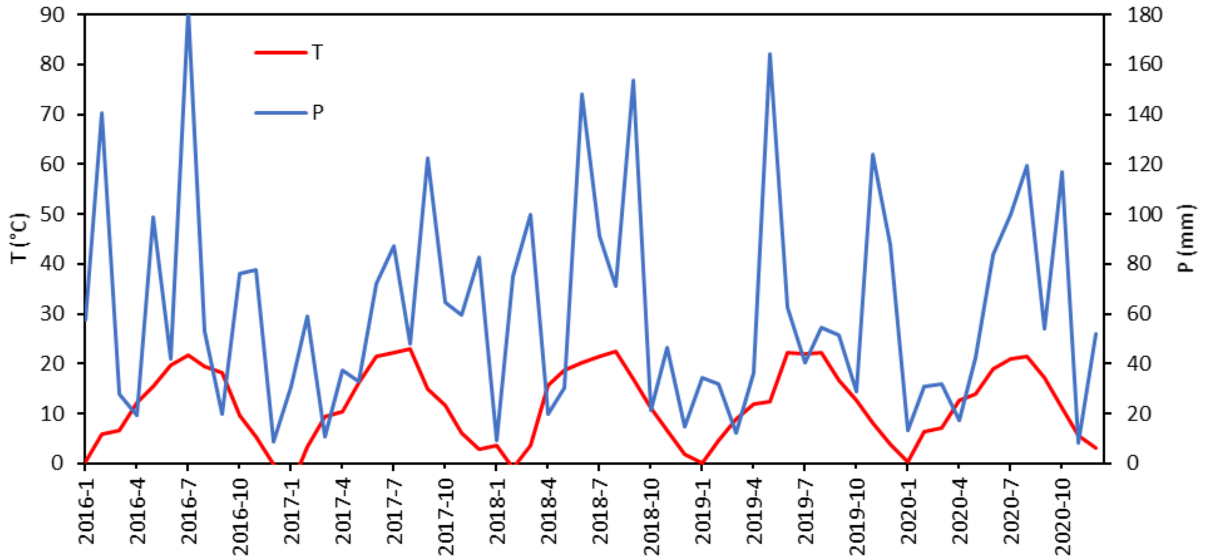

Figure 1. Monthly averages of air temperature (T) and sums of precipitation (P) measured at Sümeg between 2016 and 2020

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:

$$\mathrm{TBM} = \mathrm{a} \times \mathrm{DBH}^{\mathrm{b}}, \quad (1)$$

Where:

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

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

3 RESULTS

3.1 Results of site survey

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

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

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

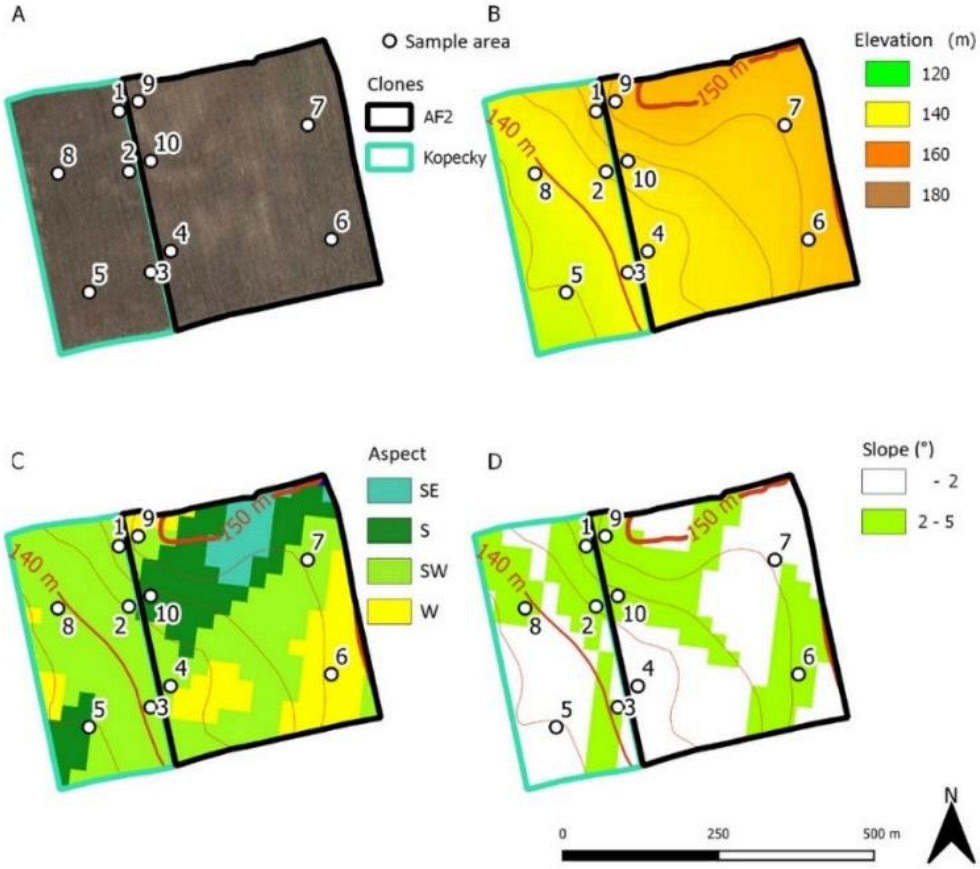

Figure 2. Maps of the research area (A – location of the samples areas, B – elevation map, C – Aspect map, and D – slope map)

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

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

3.2 Results of the biomass estimation

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

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

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

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

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

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

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

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

3.3 Effects of site parameters on tree growth

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

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

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

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

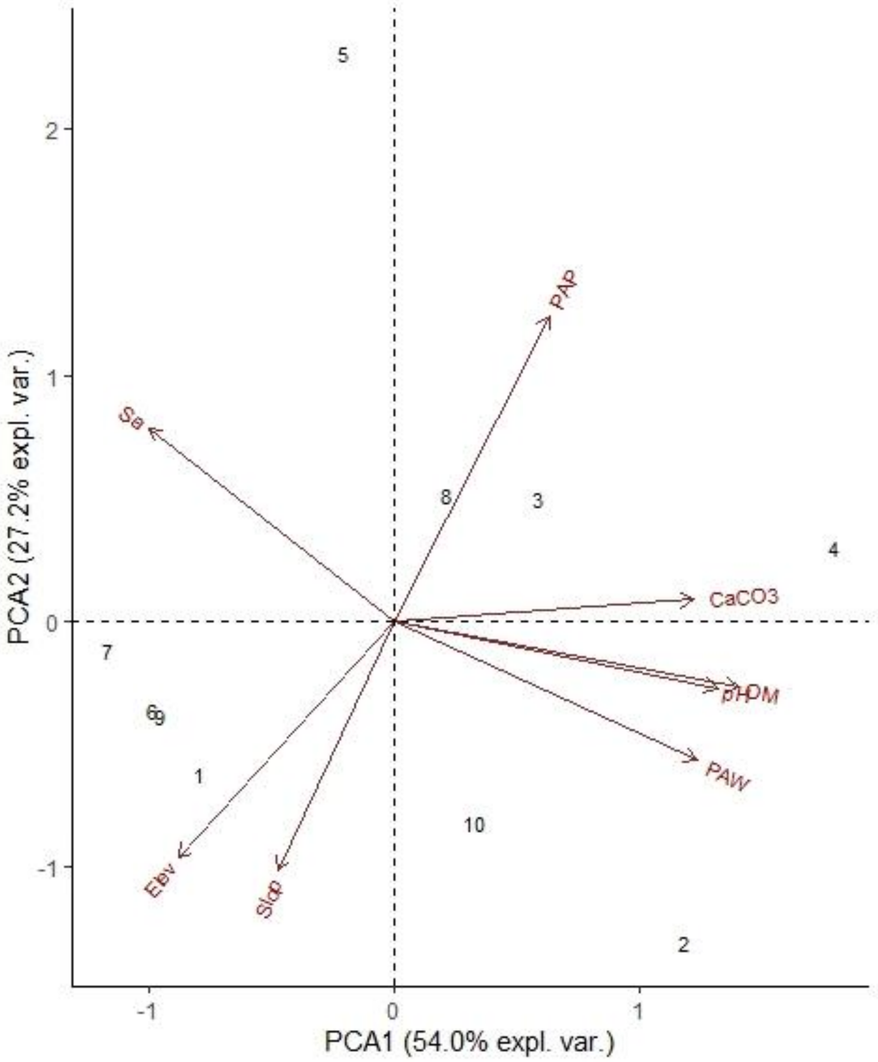

Figure 3. Ordination diagram of the PCA (Elev – elevation, Slope – slope, OM – organic matter, PAP – plant available phosphorus, Sa – sand fraction, and PAW – plant available water)

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

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

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

4 DISCUSSION

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

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

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

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

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

5 CONCLUSIONS

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

Acknowledgements: This research was supported by the ÚNKP-19-3 New National Excellence Program of the Ministry for Innovation and Technology from the source of the National Research, Development and Innovation Fund.

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ACTA SILVATICA ET LIGNARIA HUNGARICA

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https://doi.org/10.37045/aslh-2022-0006 Acta Silv. Lign. Hung., Vol. 18, Nr. 2 (2022) 89–101

Social Network Analysis in Wood Industry Projects

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Abstract – The study analysed H2020 projects in the wood industry using SNA methods. It was mainly performed using R. Based on the data set from CORDIS, an adjacency matrix was constructed and used to plot the network of project participants. Various network indicators were then calculated. In search of notable distributions in network research, several statistical methods (maximum likelihood, Kolmogorov-Smirnov test, moments, bootstrapping) were used to perform a goodness-of-fit analysis on the frequencies of the degrees to verify randomness or scale-freedom. The small-world nature was also investigated. The results show that the distribution of the degrees of project participants reflects multiple effects, whereas the number of project participations per project participant follows a power distribution; thus, the scale-freedom that has been emphasised in many scientific analyses is observed. The network indicators show that the network is not small-world, with a high number of Finnish participants among the central actors.

wood industry / project / SNA / Horizon 2020

Kivonat – Faipari projektek kapcsolatháló-elemzése. A tanulmány keretében a Horizont 2020 faipari projektjeit elemeztük hálózatelemzési (SNA) módszerekkel. Az elemzés során elsősorban az R statisztikai programozási nyelv hálózatelemzési és illeszkedésvizsgálati csomagjait használtuk. A CORDIS-ból kiszűrt adatállományra építve szomszédsági mátrixot írtunk fel, amely alapján felrajzoltuk a faipari projektrésztvevők hálóját, majd különböző hálózati mutatókat számoltunk. A hálózatkutatásban nevezetes eloszlásokat keresve többféle statisztikai módszerrel (maximum likelihood módszer, Kolmogorov-Szmirnov teszt, momentumok módszere, bootstrapping módszer) illeszkedésvizsgálatot végeztünk a fokszámok gyakoriságaira, az esetleges véletlen vagy skálafüggetlen jelleg igazolására. Vizsgáltuk a hálózat kisvilágjellegét is. Eredményeink alapján a projektrésztvevőkből felépülő projektháló fokszámainak eloszlása többféle hatást tükröz, ellenben a projektrésztvevőnként projektrészvételek száma egyértelműen hatványeloszlást követ, tehát a számos tudományos elemzésben kitüntetettnek tekintett skálafüggetlenség érvényesül. A hálózati mutatók alapján a hálózat nem kisvilágjellegű, s a központi aktorok között feltűnően sok a finn résztvevő.

faipar / projekt / SNA / Horizont 2020

1 INTRODUCTION

The analysis presented in this paper is an example of SNA (Social Network Analysis). The main research objective is to draw up and analyse the networks of mainly European institutions, research institutes and companies participating in Horizon2020 projects in the wood sector using network research tools.

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The different network indicators will measure the “development” of the network, i.e. how “efficiently” the network connects participants and how much it facilitates information and knowledge exchange. This is certainly important information for businesses, research institutes and other actors in the wood industry and can point the way forward. The research focused to a large extent on the degree (number of contacts) of the network participants. The different distributions of degree numbers may indicate the nature of the networks, their design, and the logic of their operation. The study of the scale-freedom is particularly important because in many areas of social life, it is typical that few nodes have many degree numbers, or many nodes have few degree numbers. When raising R&D resources, wood enterprises, research institutes and other actors are right to want to connect with the central actors in the networks, especially in the case of scale-free networks.

After many antecedents, the study of social networks has been a major focus of academic attention since the second half of the 1990s. In Hungary, it is largely due to the works of Albert-László Barabási (Barabási 2003). Barabási’s contribution to the discipline – particularly in the field of science management and the IT implementation of existing theories – is also considerable worldwide (Barabási 2018). However, network analysis had been an important field of science for decades before that, with its maturation starting in the second half of the 1950s. The network analysis methods applied in this paper build on the results of recent decades. Therefore, we used the results of the model describing random networks/graphs (Erdős – Rényi 1960), the configuration model for networks with a fixed degree number distribution but otherwise composed of completely random links (Bollobás 1980) (Molloy – Reed 1995) (Newman – 2010), the small world model (Watts – Strogatz 1998) and the scale-free network model (Barabási – Albert, 1999).

Network analysis has a fairly well-established methodology. Some of the methods are related to different theoretical schools of thought, but from a theoretical point of view, it can be considered more as a “pattern” with a specific logic.

2 MATERIALS AND METHODS

First, the CORDIS downloadable dataset was converted into a workable relational database. It is possible to retrieve data from all Horizon 2020 projects using the database.

The pre-screening of wood projects was done using search terms, and the filtered dataset was then subjected to content analysis to reduce the dataset further. The wood production process (value chain) is featured in 197 of the 30,084 Horizon 2020 projects. (Novotni 2022) Of the 1,093 project participants, 550 were private for-profit entities, 227 were research organisations, 159 were higher or secondary education establishments, 64 were public bodies, and 93 were other organisations. The participants represent 41 countries, mostly from the European Union. The top 5 countries involved in most projects are Spain (142), Germany (119), Italy (98), France (89), and Finland (87).

A wood project (project participants’) network is treated as an undirected network, in which the direction of connection between nodes is ignored. Regardless of their various statuses, scientific collaborations are commonly thought of as undirected connections. For example, we did not consider whether the participant is also a project coordinator. The analysis was performed using the R programming language (Novotni – Tóth 2022c). The R code makes the analysis easy to reproduce.

First, the vectors to store all the pairs of connections were generated. From this, we created a matrix and then an undirected graph. The next step was to create *the adjacency matrix*. The adjacency matrix is of great importance in network research. From the adjacency matrix, we were able to draw the connection network. The number of connections in a network can be recorded in the formula:

$$PE = \frac{N(N-1)}{2}, \quad (1)$$

where N is the elements of a network. The *density* in an undirected network can be written as:

$$D = \frac{2E}{N(N-1)}, \quad (2)$$

where E is the number of edges. If all possible connections exist and everyone is connected to everyone else, the density is 1. With a density value of 0, no one is connected to anyone. Therefore, the density value is a number between 0 and 1, with higher values indicating a higher network density (Molnár 2020). The assessment of density is only straightforward when comparing networks of similar size.

Transitivity is the average probability. If a node is connected to another node and that node is connected to a third node, then our initial node is also connected to the third node (Kisfalusi 2018). Transitivity is also known as the *average clustering coefficient*, which can be derived from the clustering coefficient (the transitivity of a given node) (Barabási 2017). The clustering coefficient of the i-th node with degree k_i is:

$$C_i = \frac{2L_i}{k_i(k_i-1)}, \quad (3)$$

where L_i is the number of connections between the neighbours with k_i degree of the i-th point. Its value is always between 0 and 1. Average clustering coefficient for the whole network is:

$$\langle C \rangle = \frac{1}{N}\sum_{i=1}^{N} C_i \quad (4)$$

based on clustering coefficient. The number of nodes (N) and the number of degrees (k) can be used to calculate the *total number of connections* with the formula:

$$L = \frac{1}{2}\sum_{i=1}^{N} k_i \quad (5)$$

in an undirected network. A fundamental characteristic of a network is whether it can be classified as scale-free. A network is called scale-free if its degree distribution can be described by a power function (Barabási 2017). The essence of scale-free networks is expressed by the moments of the degree distribution. The n-th moment of the degree number distribution is:

$$\langle k^n \rangle = \int_{k_{min}}^{k_{max}} k^n p(k)dk = C\frac{k_{max}^{n-\gamma+1} - k_{min}^{n-\gamma+1}}{n-\gamma+1} \quad (6)$$

in scale-free networks. True scale-free and random networks (normal or Poisson distribution) are quite rare, and most existing networks have a variety of effects at play in their formation and evolution. Therefore, a crucial question in network research is whether we can use a distribution other than random (Poisson or normal) or power distribution to describe the frequencies of the degree numbers. In statistics, this question falls under the topic of goodness-of-fit analysis. However, we need to clarify two seemingly trivial points about degrees.

The first problem is whether to treat the number of degrees per node as a discrete variable or as a continuous variable. The number of degrees is obviously a discrete variable, but it could be much higher, or even more diverse than the current one in the case of a larger network or more intensive cooperation. Moreover, the variable moves on a proportional scale. In such cases, for example, common statistical software introduces the concept of a "discrete variable treated as a continuous variable" and suggests the use of continuous analysis methods for the discrete variable (Acock 2018) (IBM Corp. 2020). The creators of the *fitdistrplus* package for fitting distributions and the authors of its vignette treat discrete variables with many elements as continuous (Delignette-Muller – Dutang 2020). However, for fit analysis methods for more common distributions, the applicability of continuous methods to discrete variables is controversial (Clauset et al. 2009).

Whether to use population or sampling statistical methods in the analysis was a similar problem. The problems of delimiting some characteristics of woodworking projects as a population, the not necessarily complete project network, and the inherently imperfect nature of data collection justify the choice of methods that "handle" uncertainties and imperfections, e.g. bootstrapping methods in our case. The project network that we are investigating as a possible representation of all possible project networks or as a possible sample of wood projects raises much more serious sampling issues than if we consider the set of wood projects registered in Horizon 2020 as a population. For this reason, we tended to lean towards the latter throughout the analysis. Nevertheless, we also followed the advice in the literature and performed the necessary statistical tests.

The standard goodness-of-fit test question may, therefore, be modified in that case. It is unnecessary to estimate whether the population satisfies the given distribution in the sample, but (with methodological caveats and caution) to determine instead whether the population itself satisfies the given distribution.

This is not a cardinal problem if you are not looking for exact parameters but just want to confirm or reject your hypothesis about the fit (Clauset et al. 2009) (Delignette-Muller – Dutang, 2020) (Gillespie 2020). Of course, all such controversial methodological issues should be approached with great caution. We attempted to choose the methods that give reliable results for almost "any" data set and exclude methods that give large deviations.

Using a discrete variable method, we tested whether the data series follows a Poisson distribution. A χ^2 test or a maximum likelihood method can be used (and was used) to test for a Poisson distribution. The procedure chosen can be used for a sample and a group considered as a population. We also checked whether the degree numbers follow a power distribution. Because of the uncertainties in calculations, it is worth using bootstrapping methods with higher machine requirements. The bootstrapping method performs a number of back-sampling and estimation operations on the data set under consideration and then cumulates the resulting values.

The selected computer algorithm is generally used for sampling procedures. Since we treat the group as a population here, we have not modified the procedure for sampling and the algorithm handles this well. The difference between the two results would otherwise be minimal. A *Cullen-Frey diagram* (Kurtosis-Skewness diagram) showing the possible values for the most common distributions has also been produced (Cullen – Frey 1999). Since skewness and kurtosis are not robust (small parameter changes can show large variations), we chose a non-parametric (non-normal) bootstrapping procedure with $boot = 1000$ (Efron – Tibshirani 1994). This procedure gives reliable and visually well-plotted results. The graph was generated for both discrete variables and continuously treated discrete variables.

Diameter is the "path length" of the network: the maximum number of steps needed to get from one node to any other node by the shortest possible route. Networks with small diameters are called "small world" (Barabási 2006). The formula:

$$d_{max} \approx \frac{\ln N}{\ln\langle k\rangle} \tag{7}$$

describes the diameter of a network. Equation (7) describes the small-world phenomenon (Barabási 2017). Since equation (7) gives a better approximation for the average distance ($\langle d\rangle$) between two randomly chosen nodes than for d_{max} in most networks, the formula:

$$\langle d\rangle \approx \frac{\ln N}{\ln\langle k\rangle} \tag{8}$$

describes the small-world phenomenon. Thus, for a small-world, "small" means that the average path length or diameter depends logarithmically on the length of the network.

Betweenness is a measure of how critical the network location of an actor is for network cooperation and information flow. If a node lies on many paths that are minimal routes between two other actors, it is likely to play an important role in the network (Kürtösi 2011) (Freeman 1977). The betweenness of v node is:

$$g(v) = \sum_{s\neq v\neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}, \tag{9}$$

where σ_{st} is the number of shortest paths between nodes s and t, and $\sigma_{st}(v)$ is the number of paths that pass through v of these nodes. The normalized form is often used, where the expression (9) is divided by $(N-1)(N-2)/2$ for undirected graphs. The expression:

$$\text{normal}\big(g(v)\big) = \frac{g(v) - \min(v)}{\max(v) - \min(v)} \tag{10}$$

is also often used as a normalised form. In both cases, the value falls within the range [0.1]. The betweenness and the number of degrees can be used to filter the most important participants. Many other indicators can be calculated on the basis of the literature, but this article includes only the most relevant ones for the purposes of analysis.

3 THE RESULTS OF THE ANALYSIS

3.1 Drawing the connection network

The adjacency matrix results in a matrix of 760 rows and 760 columns. Therefore, the number of nodes is 760. The size of the adjacency matrix makes it impossible to publish here, so it has been made available permanently at a specific website (Novotni – Tóth 2022a).

Starting from the adjacency matrix, *Figure 1 shows* the network of connections between project participants.

The mapped network of connections alone reveals little about the nature of the network. It does show that the majority of project participants are connected, but peripheral groups and participants also exist.

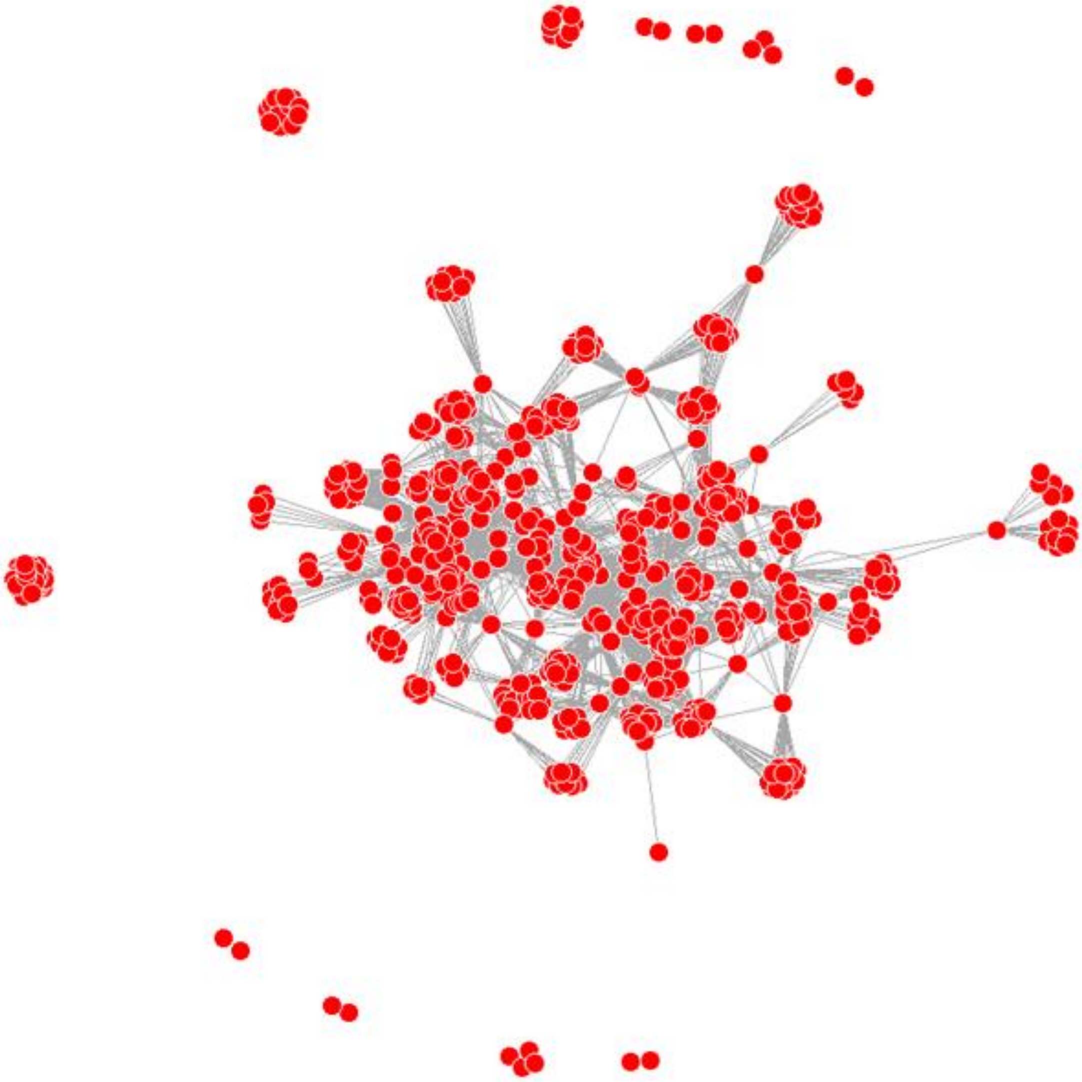

Figure 1. Network of project participants

3.2 Calculated values of network indicators and results of the fit test

The density value based on equation (1),(2) is 0.028. A reliable evaluation of the result would require the values of networks similar in size and type. The value does not seem high. There are two possible reasons for this. Perhaps the links between wood industry institutions, research institutes and companies are poorly developed. However, it is more likely that the studied networks describe the R&D intensive elite of the wood industry. Due to the finite nature of the resources, the number of project participants obviously lags significantly behind the number of potential participants.

The value of the transitivity calculated from equation (3),(4) is 0.65, which is also subject to the uncertainty as indicated in the previous indicator. However, this value seems to be high despite the uncertainty, suggesting that the "my friend's friend is my friend" phenomenon is quite pronounced in the wood industry project network. This suggests that the participants in wood industry projects are basically the “top” of the wood industry and are typically connected through established contacts, which is unfortunate for the outsiders.

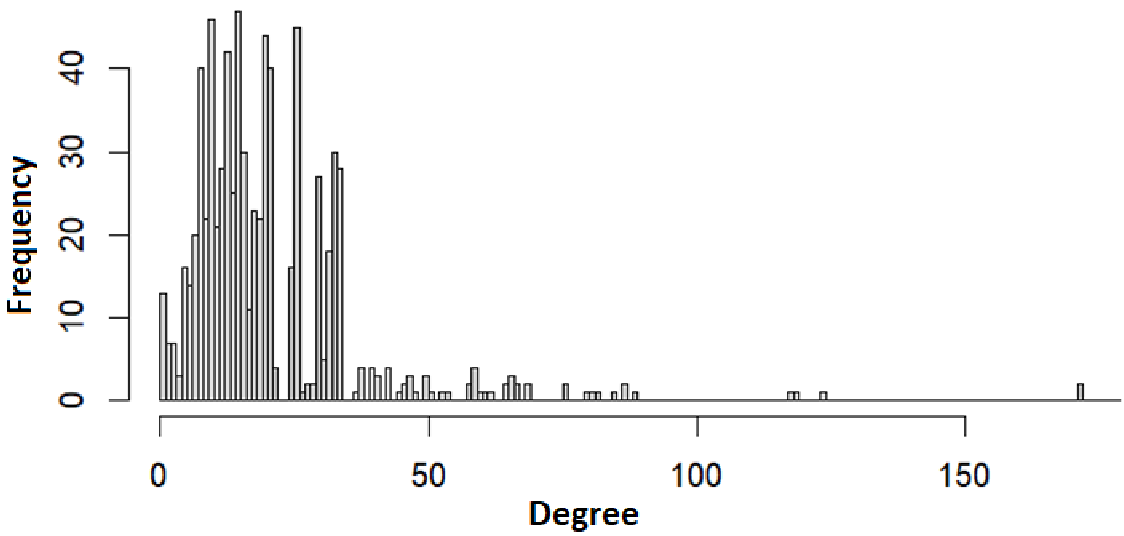

Figure 2. Frequencies of degrees

Figure 2 depicts the degrees calculated from equation (5). The result of the maximum likelihood estimation is: $G^2 = 5992.119$, $df = 63$, $p = 0$, $\lambda = 20.88421$. In the case of $\alpha = 0.05$ $c_{crit} = 82.53$ $G^2 > c_{crit}$ and $p < \alpha$; therefore, H_0 is rejected. The degree numbers are not Poisson distributed. The *rootogram*, which shows how much our empirical values should be shifted to obtain the desired distribution, confirms our results (*Figure 3*).

A Poisson distribution of degree numbers would have indicated that the majority of participants had an average degree. It is assumed that the participants in these networks are all the same, with no one in a distinguished role. By examining the formation of a network of such points, we find nodes of equal rank. The results suggest that this can be ruled out completely, as there are clearly nodes with privileged roles in the wood industry project network. This confirms our previous results.

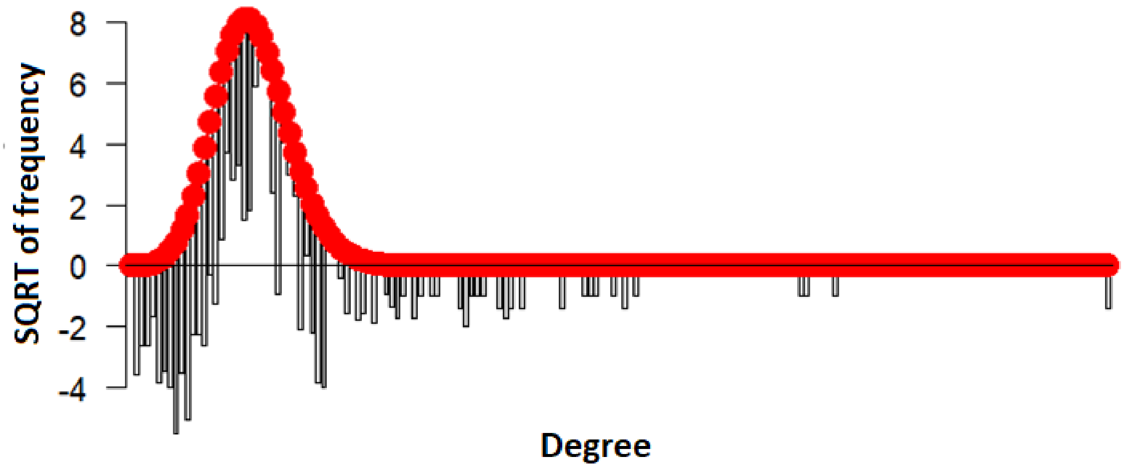

Figure 3. Rootogram of degrees

The goodness-of-fit (power distribution) test resulted in the following values: $\alpha = 4.45$, $x_{min} = 58$, $p = 0.99$. Given the high p-value obtained, we should accept H_0, but this would be a wrong conclusion since for $x \geq 58$ we can clearly say that our empirical values follow a power distribution. Therefore, H_0 is not accepted.

The values obtained with the 5000-iteration bootstrapping method are: $\alpha = 4.35$, $x_{min} = 51$, $p = 0.67$. Accordingly, the data series can be classified as power-distributed with lower confidence and a somewhat lower value, but the result does not change the fact that H_0 is rejected.

Using the Cullen-Frey diagram, we can also test the possible distribution of the degree numbers. The Cullen-Frey plot of the discrete variable confirms our previous results; the variable is not Poisson distributed. It also does not fit into the range of the negative binomial distribution (*Figure 4*).

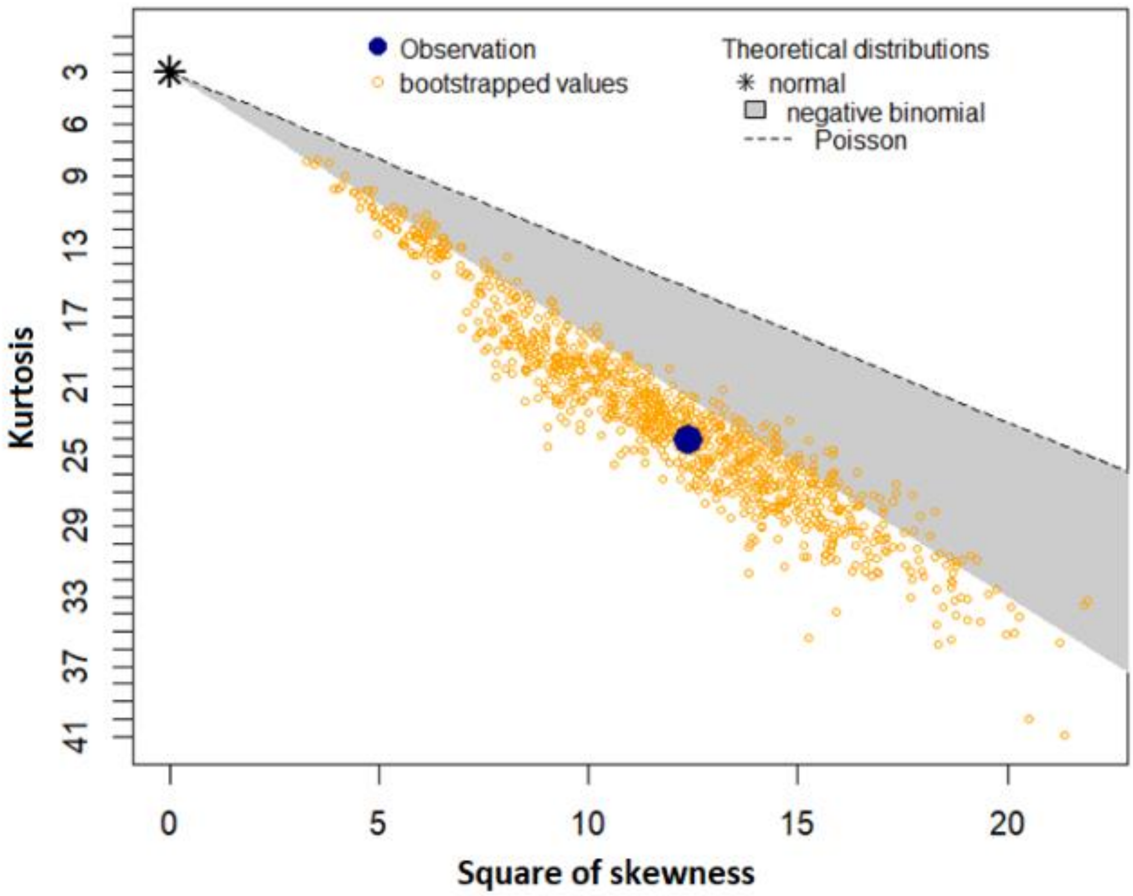

Figure 4. Cullen and Frey graph (discrete variable)

The Cullen-Frey diagram (*Figure 5*) for the discrete variable treated as a continuous variable shows that the distribution of the degree numbers lies between the gamma and lognormal distributions and outside the range of the beta distribution. A value of kurtosis much larger than 3 indicates a high peak. In such a case, the fit of the Weibull distribution is also limited (as for the other three "skewed" distributions). Distributions other than the Poisson and power distributions may suggest specific regularities that are rare in economic and social processes, but this does not appear to be the case here.

Based on the results obtained, we can assume (and this is the most likely assumption) that the "skewed to the left" distribution was influenced or shaped by a combination of random factors and factors that act towards scale-freedom. The result obtained can also be deduced from the nature of the search for partners in the projects. As the network grew, network participants tended to prefer to connect to nodes that were already recognised or had many network connections at the submission stage (preferential connection), but this also brought them into contact with other project participants, so that the frequency of the lowest degree numbers was inevitably lower than in scale-free networks. Moreover, the funding scheme favours projects with multiple actors.

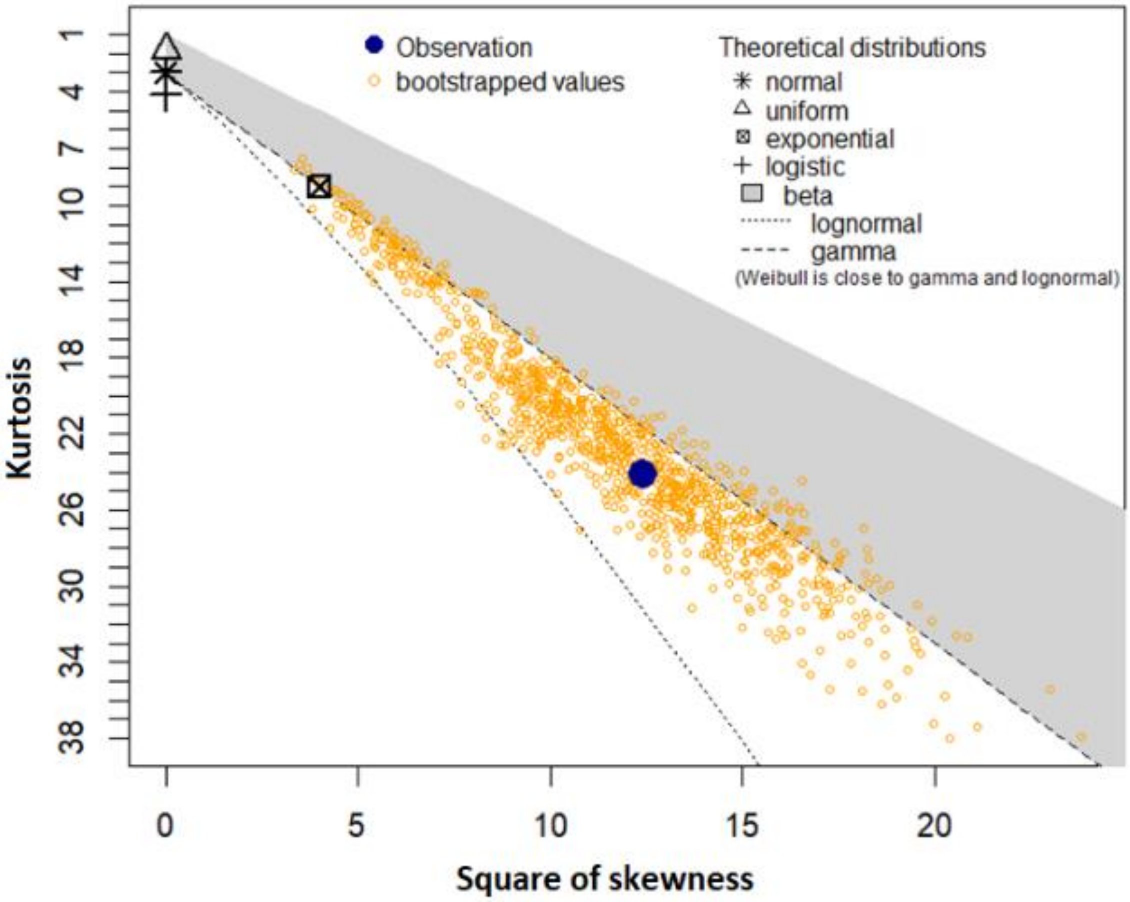

Figure 5. Cullen and Frey graph (continuous variable)

Figure 6, which shows the frequency of participation in projects per participant, seems to support this relationship. The goodness-of-fit (power distribution) test performed on these values (Novotni – Tóth 2022b) yielded the following values: $\alpha = 3.18\ (\sim\gamma)$, $x_{min} = 1$, $p = 1$.

While the distribution of degree numbers did not follow a power function distribution, the frequency of project participation showed an almost perfect fit from the initial value. In other words, scale-freedom, nowadays considered an important phenomenon in scientific analyses, applies to the frequency of project participation. (Although α is slightly higher than 3.)

The network diameter is 6. The standard deviation of the network diameter is $\sigma = 0.94$. Therefore, the relation in equation (8) is not satisfied: $6 \not\approx 2.18$ $(6 \pm 0.94 \not\approx 2.18)$. The average diameter is only 3.1, but equation (9) is still not clearly satisfied: $3.1 \not\approx 2.18$ $(3.1 \pm 0.94 \not\approx 2.18)$. The diameter is high compared to the size of the network, which suggests there are still peripheral players compared to the core in this project network, even though we can assume that we are dealing mainly with the scientific and technological elite of the wood industry and the wood industry project network obviously covers only a small part of the wood industry.

Based on the above values, the network of wood projects can be considered as small-world or not at all or only to a very limited extent. More network connections would be needed to be considered small-world. However, this does not necessarily mean that the network of contacts outside the projects cannot be considered small-scale. Rather, it is more likely that due to the average number of participants per project, barriers to entry and the attraction to those with intensive networks, small and/or non-knowledge intensive wood actors are simply under-represented in the sample and not all contacts are recorded as project contacts. The network is inherently fragmented from the point of view of the wood industry. It also hides the elites. The question is who, from a network research point of view, plays the decisive role in this network, and how far this intersects with the results of studies from other aspects.

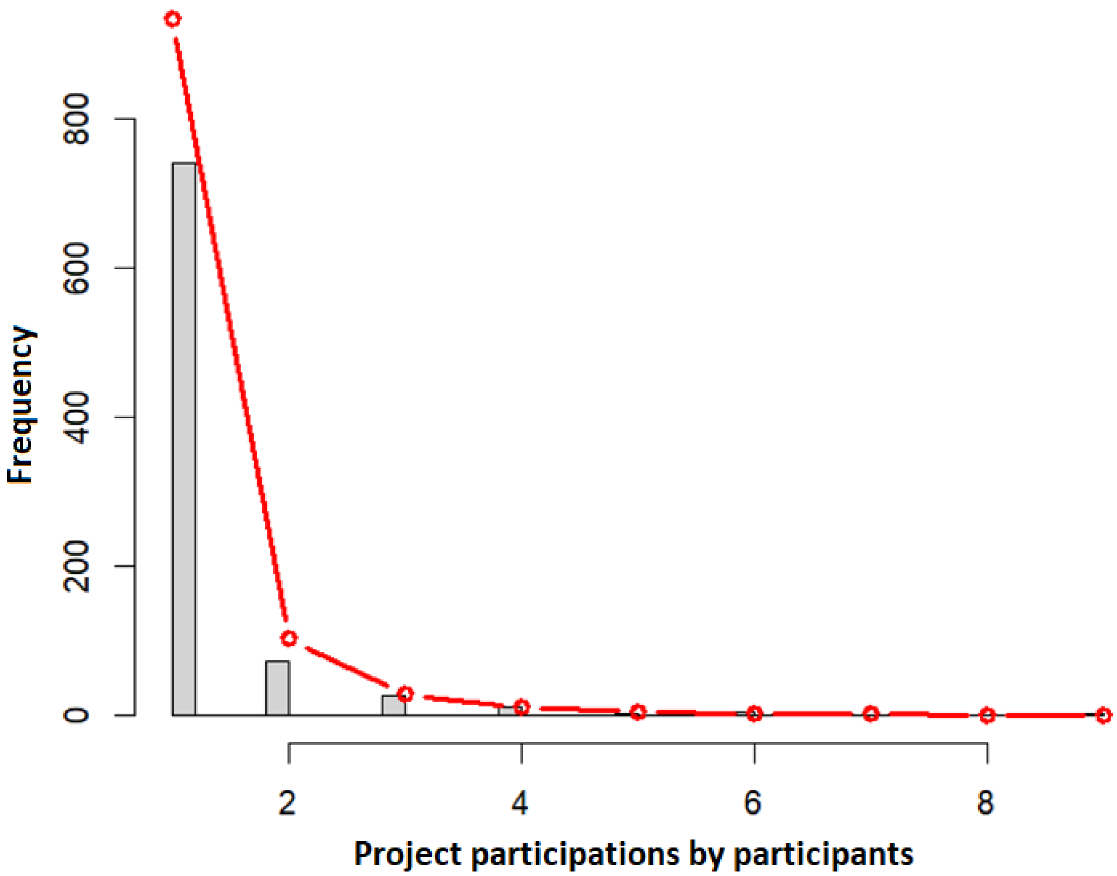

Figure 6. Frequency of participations

Table 1 lists the five project participants ranked as the most important by the degree numbers; *Table 2* by the betweenness ranking.

Table 1. Central participants by degree

Name	Country	Degree
Luonnonvarakeskus	Finland	172
Teknologian tutkimuskeskus VTT Oy	Finland	172
Fraunhofer-Gesellschaft	Germany	124
Rina Consulting S.p.A.	Italy	119
Tecnalia Research & Innovation	Spain	118

Table 2. Central participants by betweenness

Name	Country	Betweenness
Teknologian tutkimuskeskus VTT Oy	Finland	45804.83
Luonnonvarakeskus	Finland	40508.59
Fraunhofer-Gesellschaft	Germany	34836.24
Metgen Oy	Finland	18980.53
Tecnalia Research & Innovation	Spain	15980.73

There is a large overlap between the two tables. Many Finnish participants are among the central actors. Considering the weight of Finland's wood industry, the prominent role of Finnish participants is not surprising. However, based on our previous studies, most of the coordinator roles in woodworking projects were filled by participants from Spain, although Finnish participants held second place ahead of the French, Italian and British participants. However, in terms of the total number of participations in wood projects, the Finnish participants were only fifth (Novotni – Tóth 2021).

Therefore, the Finnish participants were the most important network participants, despite their relatively "low" number of participations in wood industry projects. This may indicate conscious networking, strong project participation and a long-term, knowledge-intensive strategy that goes beyond direct resource mobilisation. It is perhaps also worth noting that the two prominent Finnish institutions in the network are both research organisations and have a strong integrative role in the Finnish wood industry, which offers a potential lesson in the strategy-making process for less well-endowed but similarly small countries.

4 CONCLUSIONS

The network between participants in wood industry projects is neither random nor scale-free. On the other hand, the distribution of project participation per project participant clearly shows a power distribution, i.e. the distribution is scale-free. Meanwhile, the project network is not a small-world, i.e. there is not a sufficiently strong project network of connections in the wood sector. In any case, the central role of the Finnish participants is interesting as our analysis using other methods and other criteria did not show such dominance.

Based on the direct results, it is reasonable to assume that the real network beyond the wood industry projects may have properties approaching scale-freedom, which suggests that there is almost certainly a knowledge-intensive, vibrant network of connections at the centre of woodworking research, one that is much more central than the project network would suggest. Unfortunately, in addition to the centre, there are also a large number of peripheral players. There are many more of these than appear in the wood industry project network. Also, the nature of the projects makes some participants less peripheral. In particular, those involved in a small number of projects but otherwise with many participants.

Participating in these networks is an important objective for everyone in the industry. However, we have seen that these networks presumably describe the elite of the wood industry. Barriers to entry into these networks will continue to be a given, and the competitive advantage of entities with international project experience will continue to increase, both in terms of the chances of winning R&D funding and at the technological level. The central role of Finnish participants indicates that participants from small countries can also play a central role in wood research projects through smart strategies; however, this requires the right wood industry potential.

In the absence of such endowments, a smart strategy for those outside the elite club would be to cooperate with participants in international wood projects, not to obtain EU funding primarily but to mutually exploit scientific, technological, and business benefits. Of course, potential actors with emerging knowledge-intensive activities may target joining wood sector projects during the next funding period, but they will certainly face a difficult challenge. For those with project experience, the key question is to what extent they can build on the research and technological development carried out with EU funds to collaborate with others (especially with production companies) for mutual benefit. Finnish participants are themselves quite integrated organisations at the national level, i.e. for Hungarian project participants, R&D integration at the national level could be a first step towards strengthening international cooperation.

Acknowledgements: Project no. TKP2021-NKTA-43 has been implemented with the support provided by the Ministry of Innovation and Technology of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme.

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Comparative Analysis of Ice Break Damage in Two Börzsöny Mountain Valleys in Hungary in 2014 Based on Airborne Laser Scanning

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Abstract – Severe mechanical damage from frost and ice on trees occurred in the Börzsöny Mountains in Northern Hungary during 1–2 December 2014. The frost and ice affected 10,000 hectares overall; however, the two examined valleys suffered conspicuously different extents of damage. While the Rakottyás Valley study area had severe damage, the Pogány-Rózsás Forest Reserve suffered only moderate damage. Airborne Laser Scanning (ALS) and a field survey were utilised to assess the damage. Digital Surface Modell (DSM), Digital Terrain Model (DTM), and Normalised Digital Surface Modell (nDSM) were calculated from the dense point cloud in 3D. Elevation, slope and aspect were derived to describe site conditions. Damage thresholds were set for the ALS data (tree height < 5 m) and the ground-based damage (frequency > 90%). These were compared in a confusion matrix on a pixel scale, which showed partial agreement due to different sampling methods and ranges but also indicated that Rakottyás was more damaged (54.35% of the area) than Pogány-Rózsás (36.7%). The Total Accuracy was 0.54.

forest damage / airborne laser scanning / digital terrain model / icing

Kivonat – A 2014-es börzsönyi jégtörés által érintett völgyek összehasonlító elemzése légi lézeres letapogatás segítségével. 2014 december 1-2. között súlyos jégkár károsította a Börzsöny hegységet. A 10 000 hektárt érintő kár a Börzsöny hegység vizsgált két völgyét eltérő mértékben érintette. Amíg a Rakottyás-völgy nagy mértékben károsodott, addig a Pogány-Rózsás erdőrezervátum völgye kevésbé. A károk mértékét légi lézeres letapogatással és terepi felméréssel vizsgáltuk. A felméréshez 3D-s borított felszínmodellt (BFM), digitális domborzatmodellt (DDM) és normalizált borított felszínmodellt (nBFM) állítottunk elő nagysűrűségű pontfelhőből, melyből tengerszint feletti magasságot, lejtést és kitettséget számítottunk a termőhelyi adatok leírásához. A távérzékelt és a terepi adatokat károsodási határértékek meghatározása után képpont szinten hasonlítottuk össze egy hibamátrixban, ami részleges egyezést mutatott az eltérő mintavételi módszerek és a területi lefedettségek között. Kimutattuk továbbá, hogy a Rakottyás völgy súlyosabban sérült (a terület 54,35%-a), mint a Pogány-Rózsás rezervátum (36,7%).

erdőkár / légi lézeres letapogatás / digitális terepmodell / jégkár

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1 INTRODUCTION

The Börzsöny Mountains experienced the most severe abiotic forest damage in Hungary in the last half-century (Hirka 2015). The damaged areas include the two study areas this article covers. Sleet combined with frost characterised the weather during the damage event. Sleet fell continuously for 48 hours and froze when the temperature dropped and remained between - 0.5 – -1 ℃. The ice break caused 10,000 hectares of severe forest damage in the form of mechanical damage to branches, tops, and trunks from the ice burden on the trees. The combination of sleet and frost turned to ice and gradually accumulated on the trees over several hours. The 4–5 cm thick additional rime layer on the 3–5 cm thick ice layer, deposited from the 20–50 mm sleet, caused the most damage (Nagy 2015a). The severe top-breakage and forest reclamation triggered 100,000 m^3 of sanitary logging (Nagy 2015b).

Laser scanning technologies include terrestrial (TLS), airborne (ALS), and spaceborne (SLS) solutions. All can be efficiently applied for forest mapping and monitoring, but ALS by aeroplane is the most suitable (Király – Brolly 2006). The advantages of this method are the flexibility of flight lines, time, and sensors, and the rapidly created dense point cloud in 3D. ALS can survey several thousands of hectares in a single day within a possible accuracy of a few centimetres for elevation (Dahlqvist et al. 2011) and half a meter for tree height (or canopy height) (Kaartinen et al. 2012). ALS is ideal for measuring these two essential attributes for forest damage surveys, especially in barely accessible, mountainous areas where fieldwork is often problematic. Vastaranta et al. (2011) monitored canopy height change in Finland and reported ALS as a promising tool for snow damage surveys; however, high omission errors and acquisition costs were also experienced. Other biophysical parameters like crown diameter, biomass, or Leaf Area Index (LAI) can also be used for forest damage detection as part of forest inventory creation (Hyyppä et al. 2012).

According to previous studies, the homogenous stands in the Börzsöny Mountains with active management for economic gain suffered more crown breakage and fall damage than the forest reserve that had been unmanaged for several decades (Zoltán – Standovár 2018). With ALS data, it was possible to compare these two areas to show the difference in damage distribution in the two Börzsöny Mountain valleys. This article did not investigate discrepancies between management modes since both sites contained large damaged areas, triggering large-scale sanitary logging, which made it impossible to show differences in forest structure.

The main goal of this article was to survey ice damage in Börzsöny Mountains based on ALS and ground-based datasets. The post-event method is used to compare two valleys in the mountains that were damaged to different extents. We measured the damage via tree height and the forest damage frequency of field-based damage reports. The other goal was to investigate the site conditions (elevation, slope, aspect derived from ALS data) of the two sites, which showed similarities and dissimilarities in some geographical-ecological attributes. The reasons for the divergent observed damage intensities in the two valleys could be due to particular forest structures, management and site conditions. However, the objective of this study was to show the applicability of ALS data on forest damage sites using a post-event method on the example of the two valleys, not management surveying. The ALS survey and the field survey were both conducted after the damage, and we aimed to test if these datasets made with different methods can be compared. We also investigated possible disparities between the valleys based on the combined dataset.

2 MATERIALS AND METHODS

2.1 Study area

The study areas are located in the central part of the Börzsöny Mountains (*Figure 1a*) in Northern Hungary, belonging to Kemence and Diósjenő-Királyrét forest administrative units, more specifically, the Kemence and Diósjenő village boundaries on the borderline of Pest and Nógrád counties. The local forest manager here is Ipolyerdő Forestry Corporation. The whole of Börzsöny is protected and is part of the NATURA 2000 Network, and the Pogány-Rózsás area has further restrictions on management by belonging to the network of forest reserves (Erdőrezervátum Program 2022). The reserve consists of a core area and a buffer zone. This study examined the inner part (*Figure 1b*).

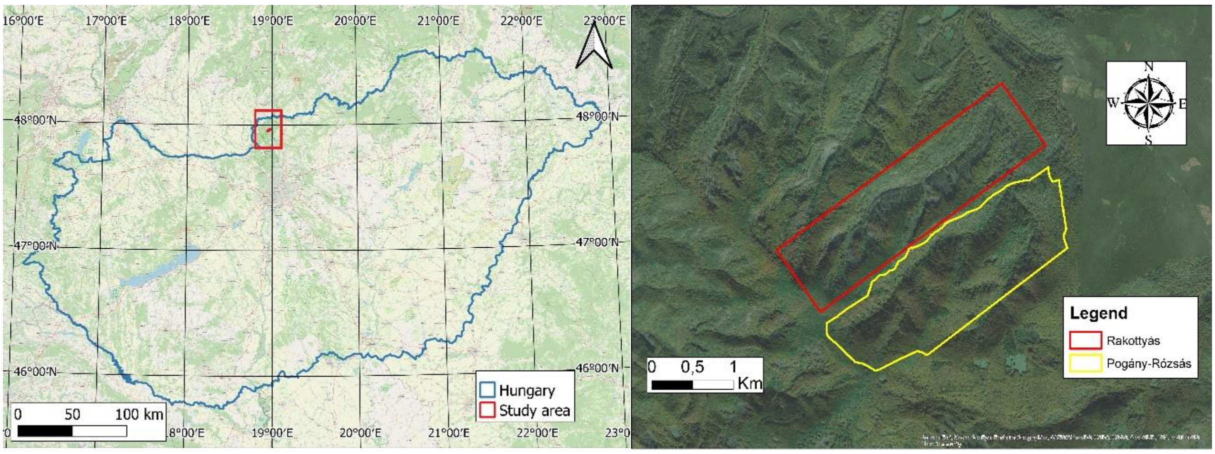

Figure 1 a, b. Börzsöny Mountains in Northern Hungary (a), which contains the two study sites, the Rakottyás (north) and the Pogány-Rózsás (south) valleys on Google Maps aerial image in 2021 (b)

The main tree species of the study area are European beech (*Fagus sylvatica*), mixed with European ash *(Fraxinus excelsior)*, sessile oak *(Quercus petraea)*, European hornbeam (*Carpinus betulus*), sycamore maple (*Acer pseudoplatanus)*, chequers (*Sorbus torminalis)*, wild cherry (*Prunus avium*), Turkey oak (*Quercus cerris*) and European larch (*Larix decidua*). In increasingly larger areas, forest management has shifted from a rotation system with clearcutting to a permanent forest cover system (Ipolyerdő 2017). The forest site conditions (according to the Hungarian forest laws) are similar in the two study sites, i.e., they belong to the beech climate zone. The soil origin type is mainly ranker (Leptosols of World Reference Base for Soil Resources), while brown forest soil (Luvisoils) occurs to a smaller extent. The soil texture is silty, and the rooting depth is deep and semi-deep. Hydrologically, the rooting depths are independent of water surplus, meaning that the forest obtains water only from precipitation.

2.2 ALS survey

The study areas were covered by an ALS survey of about 1600 hectares, from which the Rakottyás and the Pogány-Rózsás valleys cover around 630 ha. (*Figure 1*). The flight took place on 29 August 2015 (~9 months after the damage) and a point cloud was created with a Leica ALS 70-CM scanner with 30 points/m^2 density. From the digital point cloud, a Digital Terrain Model (DTM), a Digital Surface Modell (DSM), and a normalised Digital Surface Modell (nDSM) were derived. Further, the DTM was the base of slope and aspect maps.

The 3D point cloud was processed in Lastools 191111 (Isenburg 2012). The 2D rasters with 1x1 m spatial resolution were derived from the point cloud and were analysed with ArcGIS 10.7 (ESRI 2019), and QGIS 3.20 software.

2.3 Data processing

Raw ALS data processing started with the tiling of the point cloud into 100 ha large tiles in the Lastools program using the *lastile algorithm* (Figure 2) and was followed by the classification of points (echoes) into two classes: vegetation (class 1) and terrain (class 2) by *lasground*. In the next step, second class points were classified into low (0–2 m), medium (2–5 m), and high (>5m) vegetation classes (classes 3,4,5) according to their height by *lasheight*. Error points were filtered out, identified as being isolated, and having unrealistic values in class 7 by *lasnoise* based on 4 m distance and 5 points. Those points could be due to bird hits, random hardware, or software errors.

DTM was constructed from the last field echo using the *lasground* algorithm, while DSM was constructed from the first, uppermost vegetation echo according to *lashheight*. The nDSM was made of DSM using the replace z option to obtain vegetation height instead of elevation. From the 3D laz point clouds, 2D rasters were generated with *las2dem,* resulting *in* 1x1 m resolution tif files.

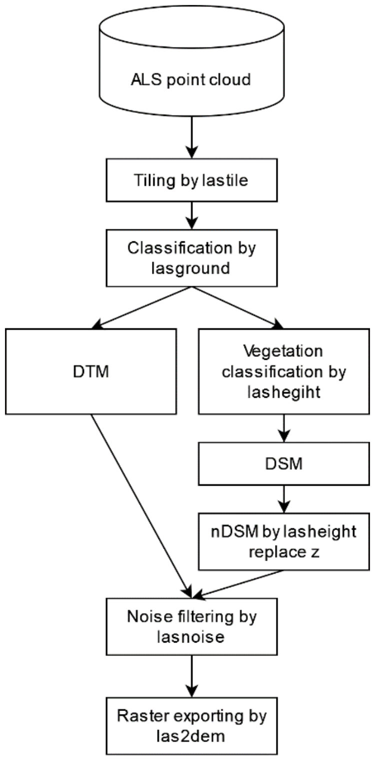

Figure 2. Flowchart of ALS data processing in Lastools.

We used ArcGIS and QGIS for raster processing and analysis. First, we merged the separate DTM, DSM, and nDSM tiles into single DTM, DSM, and nDSM rasters, respectively. Secondly, we filtered out extreme and unrealistic values in the rasters with a Gaussian filter in focal statistics (3x3 pixel rectangle) in triple-time iteration. This second filtering was needed to cease holes that remained in rasters. Thirdly, we generated slope (given in % (0-100)) and aspect (measured in degrees clockwise from 0 (north), 90° (east), 180° (south), 270° (west) to 360° (north again)) rasters based on the DTM. Comparative analyses were performed on two spatial levels, i.e., at the forest compartment level and a pixel-level based on these maps.

A database of forest compartment polygons was generated where all datasets were aggregated to the polygon level. First, we did an intersection of the Area of Interest (AOI) and a dataset of forest compartments. The ground-based data to filter the AOI provide data about site conditions and the ground-based validation was retrieved from the Hungarian National Forestry database of the Hungarian National Land Centre. The forest compartment layer was clipped by the AOI mask of Rakottyás and Pogány-Rózsás valleys based on centroids inside the polygons. The ground-surveyed forest damage from the National Forest Damage Registration System was added to the clipped polygons by joining the same forest compartments with a unique ID field. Polygons were filled with data from elevation, slope, aspect, and vegetation height rasters by zonal statistics using mean values; thus, these values were added to the attributes besides the ground-based damage and site condition information.

The ground-based dataset is from the Hungarian National Forestry database and the forest protection damage reports of the National Forest Damage Registration System (OENyR). The OENyR has data on damage frequency and intensity given for each forest compartment of Hungary, which is systematically collected and reported at least four times per year at the end of each quarter, except for quarantine pests, which must be reported immediately (Hirka 2018). The damage frequency is the number of damaged given trees compared to all trees in the same species in the compartment expressed in the percentage (0–100%), i.e. if 30 oak are damaged in a compartment containing 100 trees, then the frequency is 30%. The damage intensity shows the severity of damage and health deterioration compared to the healthy state, given in percentage (0–100%). For example, if half of the canopy is missing due to defoliation in the compartment, then the intensity is 50 %. This study used damage frequency and collected the reports from 2–19 December 2014. Based on these reports, 3,630 ha of forest in 75 compartments was damaged in the whole of the Börzsöny Mountains. From this, 1,144 ha were moderately damaged (26-60% damage intensity), 7 ha were severely damaged (61-99% damage), and 663 ha were thoroughly damaged (100% damage) (Hirka 2015). The two study sites suffered damage on 193 of 797 hectares.

Comparative spatial analysis of the two studied valleys was created at the pixel and forest compartment levels. The Zonal Statistics as Table (Spatial Analyst) function was used to calculate mean values from nDSM pixels within a forest compartment. The mean values of forest compartments were compared to the field-based damage frequency data. Regarding the pixel level datasets, the damage frequency polygons were rasterized into a 1x1 m resolution raster and with the nDSM raster, and a confusion matrix was created. The elevation, slope, aspect, and tree height rasters were also compared at the pixel level in the two valleys.

Regarding the ALS data, the damaged forest threshold was set below 5 m on the nDSM raster showing vegetation height to eliminate pixels with pioneer vegetation and to show unforested areas or fallen trees caused by ice. The ground-based report damage threshold was set to at least 90% regarding frequency. According to these rules, every pixel was reclassified. Vegetation height pixels below 5 m received the value of 0 while values above 1 were marked as damaged and non-damaged. When damage frequency reached at least 90%, the ground-based dataset received a 0; when it did not, it was labelled as 1. In the next step, the two reclassified rasters were compared with the SCP plugin of QGIS (Congedo 2021), resulting in a confusion matrix map.

In the matrix, 1 signifies damage by both methods (True Positive, TP), 2 signifies damage shown by ALS but not ground-based reports (False Positive, FP), 3 is damaged by ground-based reports but not ALS (True Negative, TN), and 4 stands for undamaged by both methods (False Negative, FN). In the confusion matrix, the true positive pixels show when the model correctly predicted the positive class (TP), while the true negatives show where the model correctly predicted the negative class (TN). False positive (FP) indicates the cases when the model incorrectly predicts the positive class. The pixel is a false negative (FN) when the model incorrectly predicted the negative class. The elements of the matrix are calculated as: P = TP+ FN; N = FP + TN; Pc = TP+ FP; Nc = FN +TN; SUM = P + N = Pc +Nc, and the matrix elements are derived as:

- Sensitivity = Probability of true positive P(TP) = TP/P
- Specificity = Probability of true negative P(TN) = TN/N
- Precision = Positive predictive value P(TP) = TP/Pc
- Negative predictive value P(TN) = TN/Nc
- Total Accuracy = Probability of accurate classification P(Acc) = (TP + TN)/SUM.

3 RESULTS AND DISCUSSION

We examined the site attributes and the extent of forest damage in both study sites. The topographic properties were partly similar in the two compared study areas. Both sites were similar in area (Pogány-Rózsás is 328 and Rakottyás 289 ha) but elevation (*Figure 3*), aspect (*Figure 4*), and slope (*Figure 5*) differed. Pogány-Rózsás was situated on higher and steeper slopes, while Rakottyás was more north-facing. Three heights (on the nDSM map) also differed due to the damage (*Figure 6*). To visualize the differences between Pogány-Rózsás and Rakottyás, elevation, slope, and aspect were compared on a radar diagram (*Figure 7*).

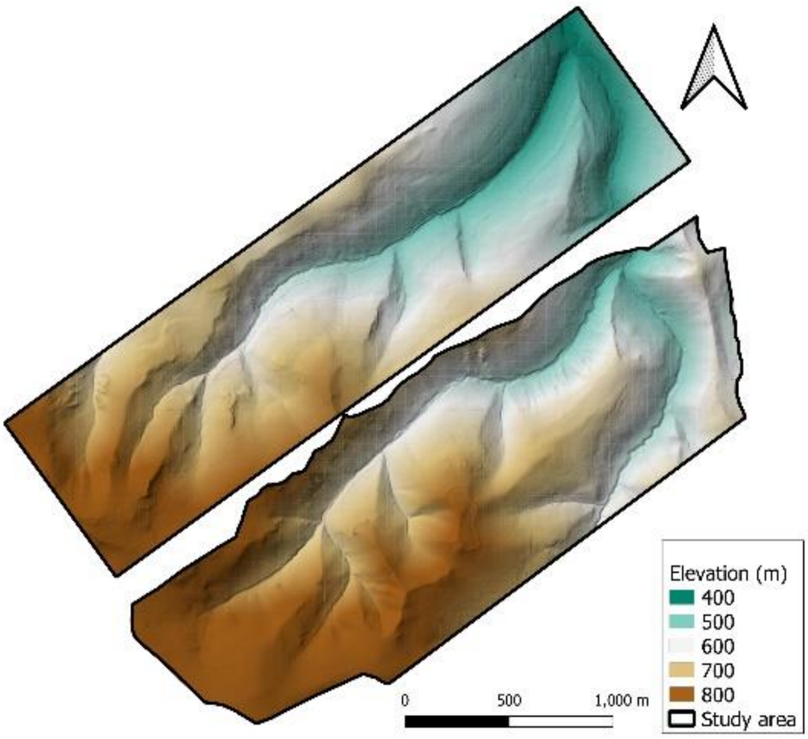

Figure 3. Elevation of Rakottyás and Pogány-Rózsás valleys based on DTM. Pogány-Rózsás is situated at higher mean elevation (696 m) then Rakottyás (632 m)

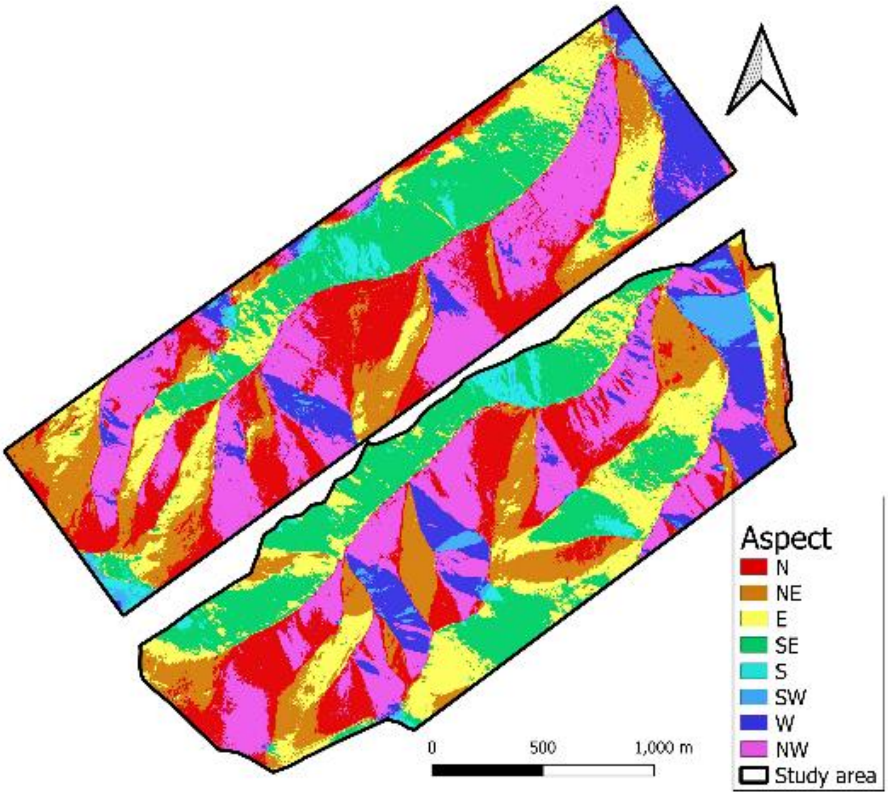

Figure 4. Aspect of Rakottyás and Pogány-Rózsás valleys based on DTM. The most typical slopes are the northerly in Rakottyás and east-facing ones in Pogány-Rózsás

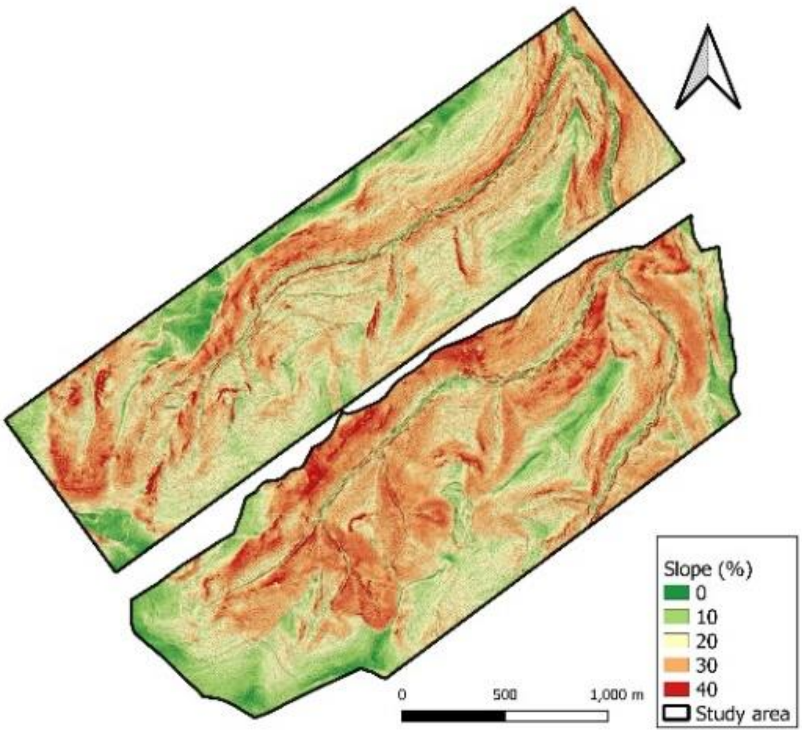

Figure 5. Slope of Rakottyás and Pogány-Rózsás valleys based on DTM. Pogány-Rózsás is slightly steeper (46% in mean) then Rakottyás (42%), but less damaged

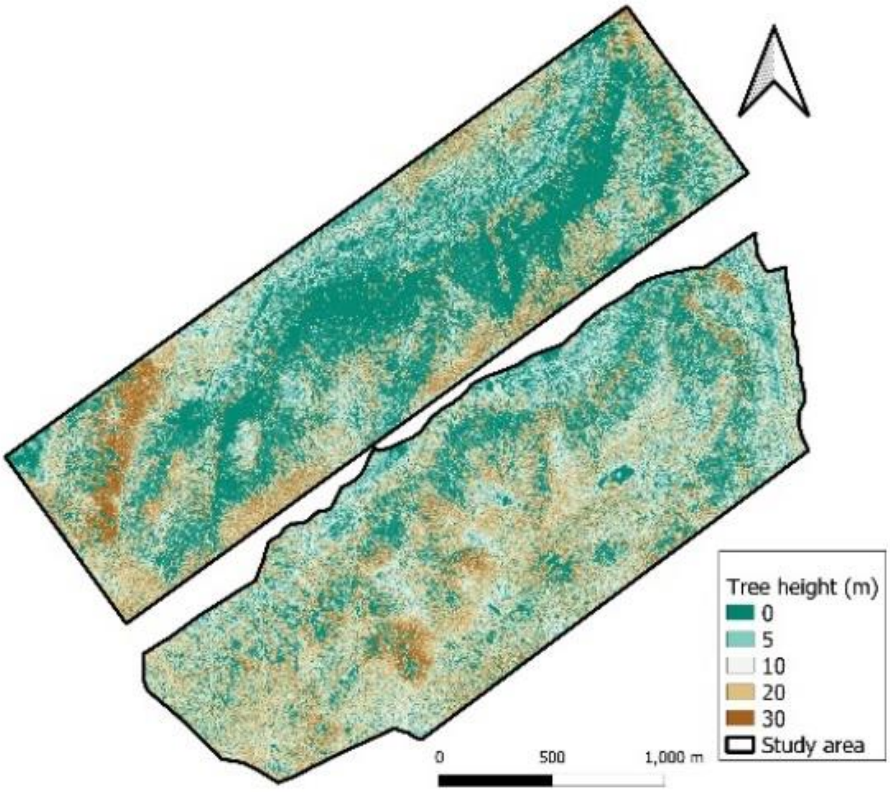

Figure 6. Vegetation height of Rakottyás and Pogány-Rózsás valleys based on nDSM. Pogány-Rózsás had more heterogenic forest heights, i.e., more small-scale differences, while the forest height in the managed Rakottyás was more homogeneous; however, this is due to the larger flat area caused by the damage

Table 1. The comparative pixel-level analysis of geographical conditions (elevation, slope, aspect) of Rakottyás and Pogány-Rózsás valleys expressed in %.

Elevation [m]			Slope [%]			Aspect		
	Pogány-Rózsás	*Rakottyás*		*Pogány-Rózsás*	*Rakottyás*		*Pogány-Rózsás*	*Rakottyás*
500	1.10	13.63	5	1.16	2.03	N	20.42	29.23
600	22.11	29.25	10	5.23	6.34	NE	22.45	21.38
700	30.63	29.73	20	23.78	27.55	E	24.03	22.28
800	24.83	18.75	30	43.95	48.97	SE	29.92	23.63
800 <	21.33	8.64	30 <	25.89	15.11	S	3.18	3.49
						SW	3.83	2.46
						W	11.88	11.70
						NW	26.37	36.47
Total	100	100		100	100		100	100

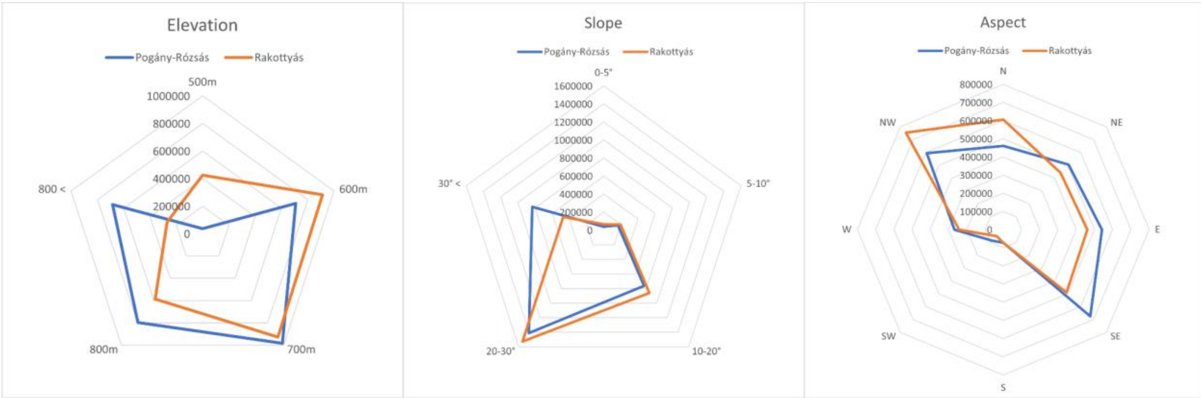

Figure 7. Elevation (a), slope (b), and aspect (c) conditions of Rakottyás and Pogány-Rózsás valleys based on DTM. The most frequently damaged slopes are the NW-facing in Rakottyás and the SE ones in Pogány-Rózsás. Steep slopes between 20–30° are the most frequent, and 700 m is the most typical height above sea level.

The comparative analysis of ground-based datasets provided information about the sixty forest compartments. The analysis was based on the damage ratio calculated from the damaged area compared to the total forest compartment area (*Table 2*) (*Figure 8*) according to the Hungarian Forest Damage Database. The comparison revealed that the Rakottyás Valley suffered moderate damage in eight forest compartments where the damage ratio was between 40–60%, while Pogány-Rózsás suffered severe damage (60–100%) in 12 forest compartments. In Pogány-Rózsás forest reserve, more damage was registered on the ground; however, according to the remote sensing method (RS), it was less damaged than Rakottyás. Nonetheless, the number of compartments is not directly or practically comparable because Pogány-Rózsás contains almost twice as many polygons as Rakottyás. Despite this, the compartment sizes are significantly larger in Rakottyás. In addition, several compartments are only slightly damaged (0-20% damage ratio) here, but their number is significant.

Table 2. Comparative analysis of Rakottyás and Pogány-Rózsás valleys based on ground-based damaged data.

Damage ratio (%)	*Rakottyás* Forest compartments (pcs)	*Pogány-Rózsás* Forest compartments (pcs)
0–20	11	24
20–40	2	2
40–60	8	1
60–80	0	5
80–100	0	7
Total	21	39
Total area (ha)	289.41	327.65
Damaged area (ha)	82.2	111.08
Damage ratio (%)	28.4	33.9

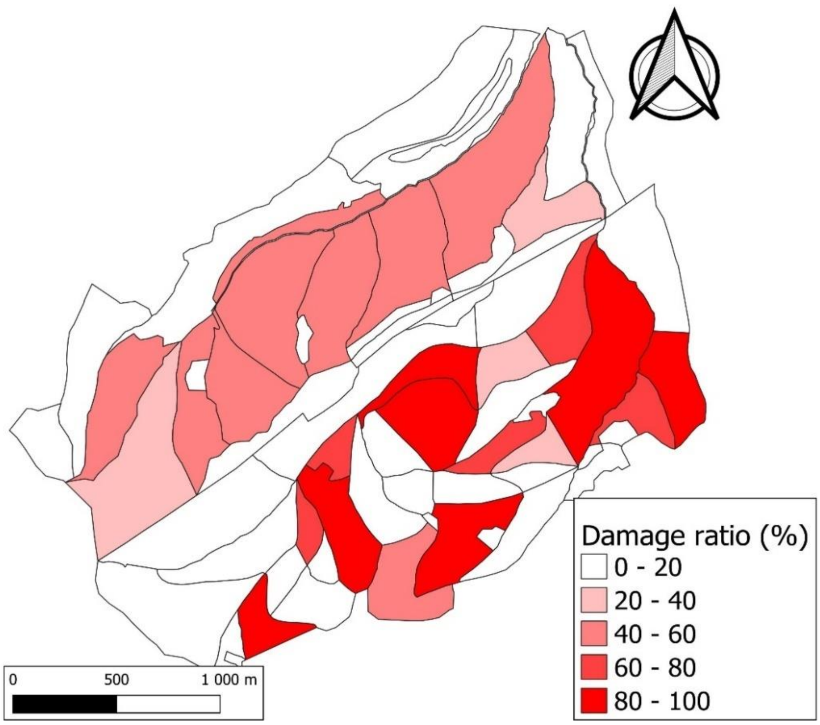

Figure 8. Ground-based damage ratio in Rakottyás and Pogány-Rózsás valleys. The difference between the damage severity and the size and number of compartments is visible in the two valleys.

The pixel-level damage analysis of ALS data was completed to compare the reclassified nDSM raster and the ground-based reports. The confusion matrix showed the precision, negative predicted values, sensitivity, specificity, and total accuracy (*Table 3*). The ground-based and RS-based methods partly agreed on the damage, which can be seen in *Figure 9* and explained by several factors.

Table 3. Confusion matrix of remotely sensed (ALS) and field-based datasets

		Predicted class			
		Positive (pixels / %)	Negative (pixels / %)		
Actual class	Positive (pixels / %)	1,514,889 / 26	1,138,339 / 19.6	0.57	Sensitivity (%)
	Negative (pixels / %)	1,518,346 / 26.1	1,650,833 / 28.4	0.52	Specificity (%)
		0.50	0.59	0.54	Total accuracy (%)
		Precision (%)	Negative predicted value (%)		

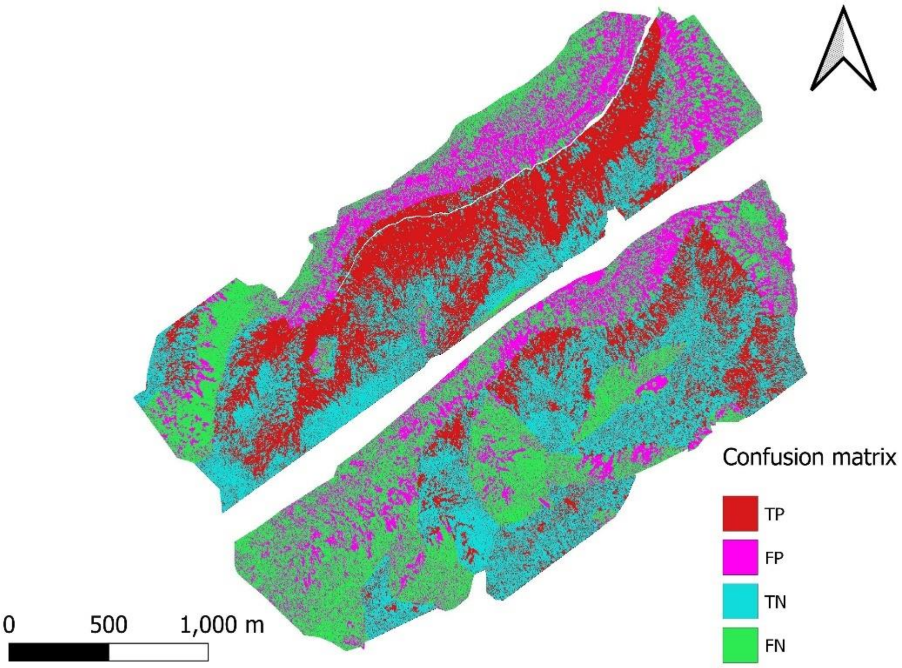

Figure 9. Confusion matrix of ALS and ground observed damage in Rakottyás and Pogány-Rózsás valleys. The colours indicate damage detected by both methods (red), by ALS (purple), by ground-based survey (cyan), and by none of the methods (green).

Based on this classification, at least one method showed damage 71.7% of the area, while both methods showed damage 26%. However, the category of no-damage covers a quarter of the AOI with 28.4%. The large average size of forest compartments, the threshold of ALS damage, and the method of ground-based data collection could all be reasons for this. The average size of the forest compartments in both valleys is large, in Pogány-Rózsás, it is 7.7 ha and 13.5 ha in Rakottyás. The average for the two study sites is 10.6 ha, but some compartments reach up to 27 ha. Since the ground-based data covers all forest compartments and do not specify the exact location of the damage, the datasets result in coarse resolution data compared to high-resolution 1x1 m rasters from ALS, which causes problems with pixel matching. The full compartment level surveying is a weakness of the ground-based dataset. The moderate precision (0.5), specificity (0.52), sensitivity (0.57), and total accuracy (0.54) could be explained by that.

When compartments were compared to each other on a pixel scale of ALS data in the two valleys that both field and ALS data covered, Rakottyás exhibited 54.3% damage, while Pogány-Rózsás exhibited only 36.7% (*Figure 10*). Thus, the 5 m ALS damage threshold successfully uncovered the difference between the valleys (*Table 4*). The difference could be attributed to stand differences. Rakottyás had even-aged stands, similar mean height, and a rotation system, while Pogány-Rózsás contained uneven-aged and more natural stands, which suffered less damage; however, this was not surveyed separately.

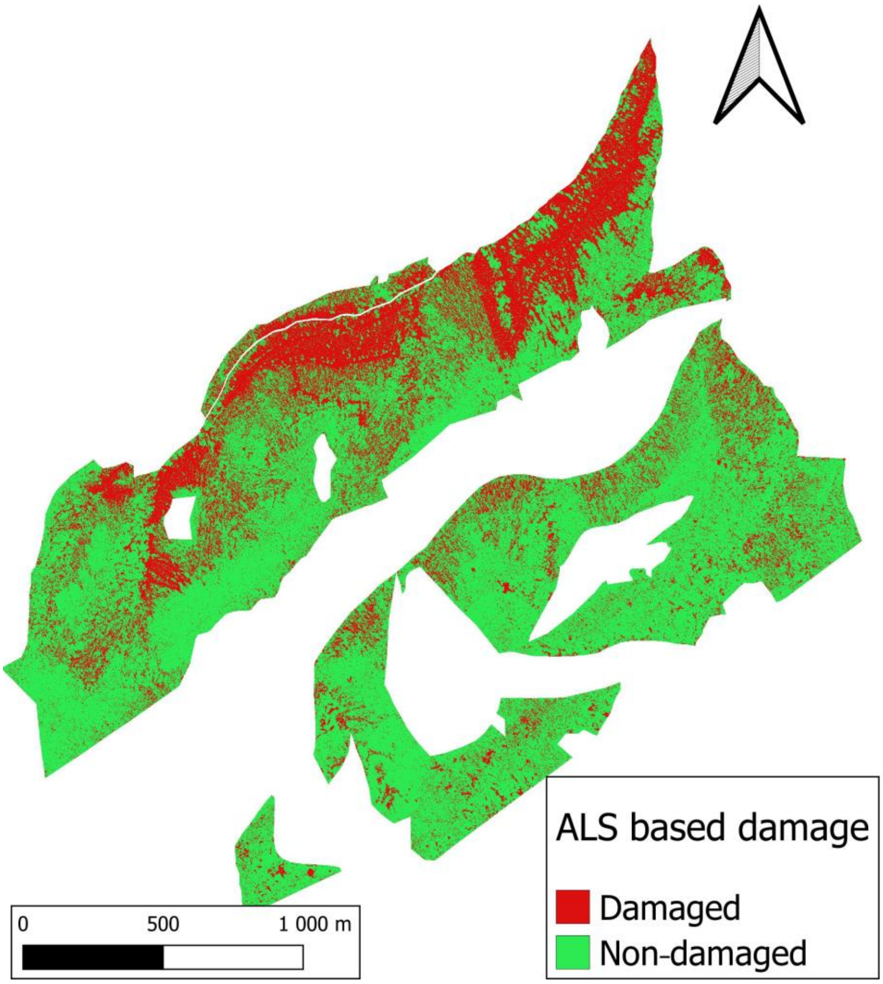

Figure 10. Comparison of two valleys on pixel scale of ALS damage data, where Rakottyás showed significantly more damage (54.35%) than Pogány-Rózsás (36.74%)

Table 4. Comparative damage survey of the two valleys on a pixel level based on ALS and field-based datasets.

Rakottyás			*Pogány-Rózsás*	
Value	Pixel count	%	Pixel count	%
0	1,439,331	54.35	1,115,011	36.74
1	1,208,880	45.65	1,920,283	63.26
Total	2,648,211	100	3,035,294	100

The different scale of the two datasets remains a problem, but the comparison accuracy could be increased with the aggregation of ALS data at the forest compartment level with which the field survey was created. For this, the ALS-based damage values (0 and 1) were aggregated with a majority filter for compartments to be directly comparable to field reports constructed at that level. In Pogány-Rózsás, 15 of the 21 compartments were damaged by both methods, while in Rakottyás this ratio was 26 of 39, resulting in 71.43% and 66.67 % accuracy, respectively.

Regarding the terms of comparative analysis, it would have been desirable to have two ALS datasets, one taken before the damage (pre-event) and one after (post-event) and compare them to show changes. Since pre-storm ALS data was unavailable, we could not compare the pre-state and post-state in the same manner Honkavaara et al. (2013) did in their study. However, we managed to show the applicability of ALS data on forest damage sites using only the post-event dataset. Chirici et al. (2018) utilised similar methods to assess forest windthrow damage in Italy using single-date, post-event ALS data, and found a 63% relative standard error when ALS was compared to a field survey in total volume estimation. They recommend the method because it is more efficient than fieldwork and provides satisfactory estimates with a given uncertainty. Notwithstanding, ALS-based snow damage detection in Finland with a bi-temporal dataset proved more accurate (78.6%) with 5x5 m pixels (Vastaranta et al. 2011). In addition to abiotic damage such as snow break or windfall, the bi-temporal method can detect biotic damage as Solberg et al. (2006) proved with LAI-based defoliation caused by insect gradation in Norway where the field-measured and ALS-based Leaf-Area Index (LAI) showed a strong correlation (R^2 = 0.87–0.93).

Although ALS in operation forestry is still rare, it has been employed several times in Norway. Noordermeer et al. (2020) used site index mapping (based on tree height at a given age) and forest disturbance classification, and Næsset (2007) evaluated methods for stand-based forest inventory where point clouds were used to predict six biophysical stand variables based on regression equations in forest planning. Both studies presented promising results. They report a total accuracy of 87–94 % for forest disturbances and 3–13 % standard deviation for tree height, basal area, and timber volume estimation compared to field-based measurements.

In addition to ALS, other RS methods like Synthetic Aperture Radar (SAR) can be also utilised to monitor ice break. Zoltán et al. (2021) applied Sentinel-1 for the same damage event in Börzsöny and revealed a 65.7 % overall accuracy albeit with a significant crown loss overestimation (55–58%).

Certain aspects of field surveys like determining soil properties could also be interesting since it could be connected to the ice damage. A shallow ranker soil is more likely prone to this type of damage compared to brown forest soil with deeper rooting depth; however, as these site conditions showed, elevation, aspect and slope have greater significance. The most severe damage occurred at particular elevations (600–700 m), slopes (2–30°) and aspects (N, NW).

4 CONCLUSIONS

The combined ALS and ground-based method successfully showed the ice break damage in Börzsöny Mountains. However, the significant differences experienced in the surveyed damage based on different methods tend to originate in the various methodologies. One reason is that the ground-based survey registered whole compartments as damaged ones regardless of the extent of the damage. On the other hand, ALS remote sensing utilises large-scale digital maps showing the exact location of the damage. Another reason for differences resides in the presence of obstacles in a ground survey. These obstacles include difficult accessibility on steep terrains, compartments containing many fallen trees, dangerous road conditions, unfavourable weather, or a lack of human resources. These difficulties often make it impossible to complete a survey, leading to damaged compartments with no field data. Although RS methods provide a solution to these issues, the cost of RS is significantly higher on smaller scales. Consequently, the combination of both methods provides the most suitable way.

Regarding larger scales, RS could offer much faster, even semi-automatized, advanced technology for forest damage surveying. Moreover, novel algorithms can increase accuracy. An ALS survey can be completed in a single day or a few days after the forest damage has occurred. The software used offers increasingly automatized methods, ensuring that data acquisition, processing, and evaluation can be performed in days, rather than over the course of months as is often the case with fieldwork. Furthermore, fieldwork requires far more organisation and human labour. RS and artificial intelligence offer effective ways to ameliorate this labour intensity.

The damage threshold offers another probable reason for differences. We chose a threshold below 5 m for damaged forests in connection with vegetation height because of the nine-month time difference separating the damage event and the survey. This period is nearly equivalent to an entire vegetation season, during which pioneer vegetation tends to grow quickly. The subjective threshold is intended to mean the difference between the constant height within a stand, which is supposed to be a healthy forest and the damaged part of the stand. The artificial intelligence-based algorithms could also help to improve thresholds by making them more objective and reveal real differences. They could also help to more accurately extrapolate datasets like tree height measurements of all trees on the field, which are not available evenly for whole study areas. It would also be desirable to study the event on two datasets (pre-and post-event) supported by artificial intelligence to detect forest structure and changes in it due to the damage. This approach could help to detect top- or branch breakage, which the current study did not investigate. Further research into such breakages is required to include them in damage surveys.

Acknowledgements: We wish to thank Anikó Hirka (Hungarian Forest Research Institute) for providing data on the Forest Database and Forest Protection Damage Reports of the Hungarian National Forest Damage Registration System. We also thank Svein Solberg from the Norwegian Institute of Bioeconomy Research (NIBIO), Zoltán Somogyi (Hungarian Forest Research Institute), Ferenc Lakatos (University of Sopron) for the advice and correction on the manuscript, and the University Foreign Language Centre of the University of Sopron for proofreading services. This article was made in frame of the project TKP2021-NKTA-43 which has been implemented with the support provided by the Ministry of Innovation and Technology of Hungary (successor: Ministry of Culture and Innovation of Hungary) from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme. The article was also funded by EFOP-3.4.3-16-2016-00022 "QUALITAS Qualitative higher education development in Sopron, Szombathely and Tata" project at University of Sopron, Hungary.

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https://doi.org/10.37045/aslh-2022-0008 Acta Silv. Lign. Hung., Vol. 18, Nr. 2 (2022) 119–127

Measurements of the Load-bearing Structural Aspects of Pannónia Poplar from Sites in Western Transdanubia, Hungary

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Abstract – This study summarises the test results of Pannónia poplar (*Populus* × *euramericana* cv. Pannónia) originating from three plantation sites in Győr-Moson-Sopron County in the Western Transdanubia region of Hungary: Újrónafő 11G, Győr 540B, and Kapuvár 35A. The research primarily aimed to clarify the characteristics of radial growth depending on the plantation site and to predict the selected physical and mechanical properties of the xylem. Measuring the time-of-flight (TOF) in trees was performed with a non-destructive test technique using a "Fakopp" TreeSonic device. The stress wave velocity (SWV) values calculated from TOF data are significant in estimating the dynamic modulus of elasticity (MOE) of the xylem and, therefore, in the prediction of timber suitability for structural applications. During the on-site measurements, 50 trees – as random samples from every site – were investigated to determine the diameter at breast height (DBH) and the stress wave velocity in sapwood parallel to the grain. In addition to the non-destructive measurements, the laboratory analysis of the xylem from harvested logs (three logs per site, random sample) was also performed to determine the radial growth rate and density. The one-way ANOVA results revealed significant differences in SWV values between certain plantation groups. The difference between the average values of young and old plantations is 136.8 m/s, which is a significant difference. Similar findings occurred for the middle-aged and old plantation trees. The average values of the young and the middle-aged trees can be considered the same at the 0.05 level of significance. We also established that the trees in the young (22 years old) plantation site, Újrónafő 11G, planted with the closest spacing (3 m × 4 m), had the lowest average diameter of breast height naturally and showed the highest average value of SWV. Nevertheless, the sap- and heartwood samples from this plantation site had the highest average density values in a normal climate; therefore, the highest dynamic modulus of elasticity of the xylem can be expected in logs originating from this plantation site.

***Populus* × *euramericana* cv. Pannónia / stress wave velocity / diameter at breast height / density / dynamic modulus of elasticity / load-bearing structural timber**

Kivonat – Nyugat-Dunántúli ültetvényekről származó Pannónia nyár teherviselő szerkezeti szempontok szerinti mérései. A jelen tanulmányban három, név szerint Újrónafő 11G, Győr 540B és Kapuvár 35A, nyugat-dunántúli, Győr-Moson-Sopron megyei Pannónia nyár (*Populus* × *euramericana* cv. Pannónia) ültetvénnyel kapcsolatos vizsgálati eredményeinket foglaljuk össze. Kutatómunkánkban a vizsgált ültetvényes egyedek vastagsági növekedési jellemzőinek tisztázását, valamint a fatest kiválasztott fizikai és mechanikai tulajdonságainak előrejelzését tűztük ki célul. A hang terjedési idejének (TOF) meghatározása élő fákban roncsolásmentes módon "Fakopp" TreeSonic berendezéssel történt. A TOF adatokból kiszámított hangterjedési sebesség (SWV) kiemelkedő

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jelentőséggel bír a fatest dinamikus rugalmassági modulusza (MOE) becslésében és ezáltal a szerkezeti fa minőségének előrejelzésében. A mellmagassági átmérő (DBH) valamint a szijács rostirányában történő hangterjedési sebesség meghatározása érdekében 50 véletlenszerűen kiválasztott egyed helyszíni vizsgálatára került sor. A roncsolásmentes vizsgálatok kiegészítéseként kidöntött törzsek (3 törzs ültetvényenként, szúrópróbaszerű minta) fatestének laboratóriumi analízisét is elvégeztük az évgyűrűszélesség és a sűrűség meghatározására. A one-way ANOVA eredményeink alapján jelentős különbségek mutatkoztak az SWV értékekben egyes ültetvénycsoportok között. A fiatal és idős ültetvények átlagértékei között 136,8 m/s volt az eltérés, ami szignifikáns különbség. Hasonló eredményeket tapasztaltunk a középkorú és az idős ültetvényes fák esetében is. A fiatal és a középkorú fák átlagértékei 0,05-ös szignifikancia szinten azonosnak tekinthetők. Ugyancsak megállapítottuk, hogy a fiatal (22 éves), legsűrűbb hálózatban ültetett (3 m × 4 m) és egyben legkisebb mellmagassági átmérő átlagértékkel rendelkező Újrónafő 11G ültetvény egyedei mutatták a legmagasabb SWV átlagértéket. Kiegészítésként meg kell azonban említeni, hogy ugyanezen ültetvényről származó szijács és geszt minták rendelkeztek a legmagasabb átlagértékekkel a normál klímán vett sűrűség vonatkozásában is, ezáltal a fatest legnagyobb dinamikus rugalmassági modulusza is várhatóan ennél az ültetvénynél jelezhető előre

***Populus* × *euramericana* cv. Pannónia / hangterjedési sebesség / mellmagassági átmérő / sűrűség / dinamikus rugalmassági modulusz / teherviselő szerkezeti fa**

1 INTRODUCTION

Willows and poplars belong to the same *Salicaceae* botanical family. About 40 species of the genus *Populus* exist in the northern hemisphere. Sections such as Aigerios and, partially, Leuce in Hungary (Tóth – Erdős 1988) and Aigeros, Leuce, and Tacamahaca in Austria (Nebenführ 2007) are important in forestry. The European black poplar (*Populus nigra* L.), the American black poplar (*Populus deltoides* Bartr. Ex Marsh.), and their clones (*Populus* × *euramericana*) are systematically assigned to the poplar section Aigerios. The Pannónia poplar (*Populus* × *euramericana* cv. Pannónia) is an artificial variety hybridized by Ferenc Kopeczky, a forest scientist at the Hungarian Forest Research Institute (ERTI) in Sárvár. According to Tóth and Erdős (1988), the parent trees of Pannónia poplar were *Populus deltoides* S-1-54 Belgium and *Populus nigra* Lébény 211. The rapid growth rate of Pannónia poplar is similar to variety 'I 214' (*Populus* × *euramericana* cv. 214) and can reach a density that is similar to *Populus* × *euramericana* cv. Robusta (Molnár – Bariska 2006).

Industrial poplar breeding began in Hungary in the 1920s, mainly on the Danube floodplain. Tóth and Erdős (1988) refer to the data to indicate a marked increase (more than 115,000 ha) in the total area of Poplar populations between 1949 and 1986. Thanks to its outstanding characteristics, the ‘Pannónia’ poplar variety was one of the most important planting stocks in Hungary in the 1990s (Tóth 2006). Papp and Horváth (2016) summarised the relevant scientific data, including the domestic research activities and results. Their study emphasised that although poplar research with other target species was advanced in Hungary, the number of site-specific, material scientific studies on load-bearing structural properties of Pannónia poplar are minimal.

According to Schlosser et al. (2012), many studies on replacing conifers with poplars were conducted in the 1960s and 70s, particularly in institutions such as the Wood Research Institute (Faipari Kutató Intézet) in Budapest. The physical and mechanical properties of other hybrid poplars like ‘Robusta’, ’Marilandica’ and ‘Serotina’ varieties were found to be suitable for construction purposes. The apex of contemporary research was designing and constructing an 800 m^2 hall built of poplar raw materials in Velence, Hungary in 1974, which remained in use until 2012 and retained a surprisingly sturdy wood structure.

As a raw material, Pannónia poplar has a wide range of opportunities for industrial utilisation, including furniture, cellulose, fibreboard, packaging, or matchstick production (Tóth 1996). The Institute of Wood Science, the predecessor of the Institute of Wood Technology and Technical Sciences in Sopron, analysed the Pannonia poplar samples to identify the effects of thermal modifications in dry, atmospheric air (Horváth 2008) and in vegetable oils (Bak 2012) on changes in the physical, mechanical properties and the protective effectiveness against *basidiomycetes*. These researchers also determined static compression and bending strength values (among others) of untreated small-sized samples in a normal climate. Their results were similar to the spruce data (*Picea abies L.*) in the literature, which is the most frequently used timber in roof construction in Hungary. The modulus of elasticity in three-point bending tests of samples cut out from 13-year-old Pannónia poplar trees was the same as the lower value reported for spruce in the scientific literature. The above studies investigated the xylem of juvenile wood, which cannot represent the performance of mature wood. Németh et al. (2015) called attention to the high variation of mechanical properties of different poplar hybrids from various sites and recommended timber grading before application.

Research at the University of Sopron (formerly: University of West Hungary) verified that the xylem of the first 20–22 annual rings in poplars did not show lower density than mature wood, which contradicts other wood species. Van Acker et al. (2016) pointed out that the fast-growing species will make higher production possible within both a sylvicultural and an agricultural framework. The study also suggested that poplar trees could offer the best potential alternative to softwood species for engineered wood products. Due to the lower natural durability of poplar wood species against degrading agents, the lifetime of poplar-based construction products is cardinal nowadays (Van Acker et al. 2020). Investigations into the properties of poplar wood species as a building material are increasing. Some of the investigated properties include durability against fungal decay (Horváth et al. 2012), wettability (Rábai et al. 2020, Brahmia et al. 2020), moisture-induced stresses (Mirzaei et al. 2017), fire-retarding properties (Habibzade et al. 2016), and bondability (Vilpponen et al. 2014, Wang et al. 2015, Konnerth et al. 2016).

2 MATERIALS AND METHODS

2.1 Plantation sites investigated

We performed the on-site investigations to gain information regarding the selected characteristics of the trees. *Figure 1* shows the relevant Pannónia poplar plantations sites of KAEG Zrt, which we chose for our non-destructive measurements in Győr-Moson-Sopron County in the Western Transdanubia region of Hungary. GPS coordinates determined the locations of these three plantation sites, marked with red, green and blue squares on the map.

2.2 Non-destructive measurement and laboratory measurements

During our research protocol, we performed the non-destructive studies on trees first. We used a stress wave non-destructive test technique with a "Fakopp" TreeSonic device to test the standing trees (*Figure 2*). The on-site non-destructive measurements were performed in September 2016. The moisture contents (MC_{xylem}) of the tree xylems were 150–170% and their temperatures (t_{xylem}) ranged from 15 to 20 ° C. The deviation of the SWV values along the grain caused by these two parameters is negligible at these levels (Moreno Chan et al. 2011).

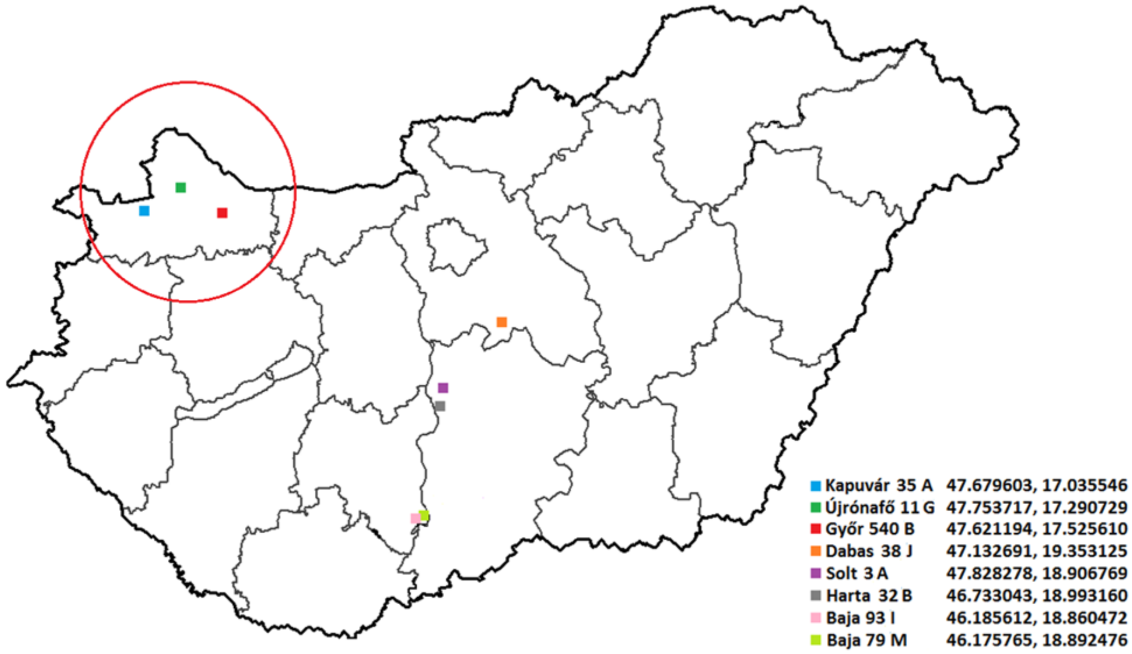

Figure 1. The relevant Pannónia poplar plantations in Győr-Moson-Sopron County (Kapuvár 35 A; Újrónafő 11 G and Győr 540 B)

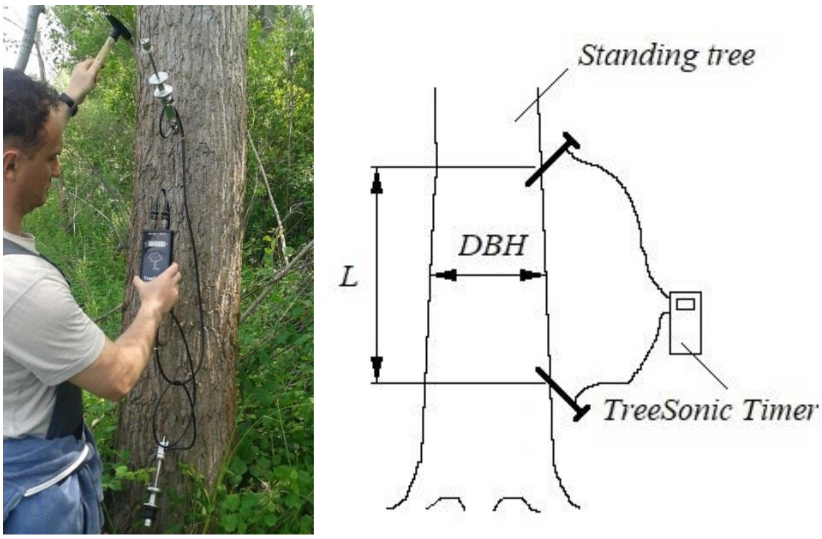

Figure 2. The time-of-flight (TOF) stress wave measurement on trees with a "Fakopp" TreeSonic device (left) and its schematic figure (right).

Fifty trees were investigated ($n_{\text{trees tested/site}}$=50) in each plantation to determine the diameter at breast height (DBH) and the stress wave velocity (SWV) in sapwood parallel to the grain. Afterwards, we performed laboratory analysis of the samples from harvested logs (three logs/plantation, random sample, $n_{logs/plantation}=3$) to determine the selected material properties. The SWS values were calculated according to the following formula:

$$SWV = \frac{L}{TOF} \cdot 10^6 \tag{1}$$

Where:

SWV:	the longitudinal stress wave velocity along the grain in metres per second (m/s)
TOF:	the time-of-flight (wave propagation time as output of “Fakopp” TreeSonic device) in microseconds (μs)
L:	the test span in metres (m).

For the moisture content (MC) laboratory measurements and the respective density, five-five specimens ($n_{sapwood\ samples/logs}$=5, $n_{heartwood\ samples/logs}$=5, radial × tangential × longitudinal: 20 mm × 20 mm × 30 mm,) were cut out from the sapwood and heartwood as bulk samples from the logs ($n_{sapwood\ bulk\ samples}=15$, $n_{heartwood\ bulk\ samples}=15$). The specimens were conditioned until reaching their weight constant in a normal climate (65% relative humidity, 20 °C air temperature).

We measured the specimen size and weight with digital calliper and a digital balance, which both had a measuring accuracy down to 0.01mm and 0.01g. The values were calculated according to the following formula:

$$\rho_n = \frac{m_n}{l_n \cdot r_n \cdot t_n} \cdot 10^6 \quad (2)$$

Where:

ρ_n:	sample density at normal climate (kg/m^3)
l_n:	sample size parallel to the grain at normal climate (mm)
r_n:	sample size in radial direction at normal climate (mm)
t_n:	sample size in tangential direction at normal climate (mm)
m_n:	sample weight at normal climate (g).

3 RESULTS AND DISCUSSION

In the case of KAEG Ltd., there was a considerable difference between tree ages recorded in the company registers and the plantation age determined upon the experimental felled logs ($n_{logs/plantation}$=3). Based on the annual rings of the logs, the trees were 22 years old in Újrónafő 11G plantation, 24 years old in Győr 540 B plantation, and 29 years old in Kapuvár 35A plantation.

3.1 Results of the non-destructive measurements

Table 1 presents the average tree diameter at breast height (DBH). The comparative statistical analysis in all cases was unavailable because of the significantly differing plantation ages. However, the DBH values of the Újrónafő 11G plantation – being otherwise the youngest plantation among the sites, with the closest spacing between trees (3 m ×4 m) – were naturally the lowest.

Table 1. Diameter at breast height (DBH) of the trees ($n_{trees\ tested/site}$=50)

DBH (cm)	Average	St. dev.	Min	Max
Újrónafő 11G (young)	21.3	3.96	15.3	30.9
Győr 540B (middle-aged)	39.5	4.17	30.9	53.2
Kapuvár 35A (old)	45.8	6.97	31.2	63.4

Table 2 presents the stress wave velocity (SWV) data in the sapwood of the standing trees. The SWV average value is highest in the young plantation (Újrónafő 11G) and lowest in the old plantation (Kapuvár 35A). The one-way ANOVA result revealed significant differences in SWV data between the different plantation groups (F(2;147)=5.859; p=0.004). The post-hoc test at the 0.05 level of significance also showed that the difference between the average values of the young and middle-aged plantation trees was not significant (21.6 m/s). The difference between the average values of the young and old plantations is 136.8 m/s, which is significantly different. A similarity can be found between the middle-aged and old plantation trees, where the difference is only 115.2 m/s.

Table 2. Stress wave velocity (SWV) along the grain in sapwood of the trees ($n_{trees\ tested}$=50, t_{xylem}=15–20 °C, MC_{xylem}=150–170%)

SWV (m/s)	Average	St. dev.	Min	Max
Újrónafő 11G (young)	4276.2	198.26	3807.1	4601.2
Győr 540B (middle-aged)	4254.6	145.96	3937.0	4601.2
Kapuvár 35A (old)	4139.4	279.01	3699.1	4854.4

3.2 Results of the laboratory measurements

The experimental logs were used to define their felling age in 2016 and to define their density. Complex statistical analysis was not recommended for the laboratory measurements because of the small sample size (three logs/plantation). However, the density values of the Újrónafő 11G young plantation were the highest in all cases. *Table 3* presents the sapwood density data at normal climate (ρ_n). Without statistical evaluation, it is evident that the data on the average sapwood density show lower differences.

Table 3. Density of the sapwood ($\rho_{n\ sapwood}$) bulk samples at normal climate ($n_{logs/plantation}$=3, $n_{samples/logs}$=5, $n_{sapwood\ bulk\ samples}$=15)

$\rho_{n\ sapwood}$ (kg/m^3)	Average	St. dev.	Min	Max
Újrónafő 11G (young)	443.7	15.84	414.0	478.3
Győr 540B (middle-aged)	427.1	27.70	337.2	483.7
Kapuvár 35A (old)	438.0	6.80	426.0	447.4

The average density values of the Újrónafő 11G heartwood samples were obviously higher than the values of samples from the other two plantations. The density values of the heartwood samples of the youngest and most densely planted trees – with the lowest DBH among the sites – exceed 500 kg/m^3 in many cases.

Table 4. The density of the heartwood ($\rho_{n\ heartwood}$) bulk samples at normal climate (n_{logs}=3, $n_{heartwood\ samples/logs}$=5, $n_{heartwood\ bulk\ samples}$=15)

$\rho_{n\ heartwood}$ (kg/m^3)	Average	St. dev.	Min	Max
Újrónafő 11G (young)	469.9	32.38	351.5	556.9
Győr 540B (middle-aged)	413.4	21.42	372.7	476.4
Kapuvár 35A (old)	395.1	28.10	363.0	442.8

3.3 The dynamic MOE expected from our results

Dynamic MOE is an important measurement for estimating stiffness in standing trees, logs, timber and small specimens. In practice, fieldwork is confined to measuring acoustic velocity, and dynamic MOE is estimated by assuming a certain value for green density (Moreno Chan et al. 2011). The relationship between the dynamic MOE, density and the SWV values of a material can be given by $E = \rho v^2$ (Divós – Bejó 2006, Moreno Chan et al. 2011).

According to the SWV values on trees and the density values of the specimens at normal climate, the average dynamic MOE of Újrónafő 11G (young) plantation is expected to be significantly higher than the values of the other two plantations (see *Table 5*).

Table 5. The dynamic MOE expected according to the average SWV- and the density values of sapwood

Expected average values	Újrónafő 11G (young)	Győr 540B (middle-aged)	Kapuvár 35A (old)
Dynamic MOE $_{sapwood}$ (N/mm^2)	>8100	>7700	>7500

4 CONCLUSIONS

The DBH test results of trees were not evaluated statistically due to the significantly different ages of the plantations. However, the average DBH values in Újrónafő 11G – the youngest plantation, planted with the closest spacing (3 m × 4 m) on different soil conditions – were significantly lower than the values of the other two plantations. The average DBH values of the 22-year-old trees in Újrónafő 11G plantation were 21.3 cm, while the DBH values of the 24-year-old logs in Győr 540B plantation (being the closest in age) were 39.5 cm (*Table 1*).

According to our one-way ANOVA results, there was no significant difference between the average SWV values of the young (Újrónafő 11G) and the middle-aged (Győr 540B) plantation groups in case of 15–20 °C material temperature, 150–170% moisture content and 0.05 level of significance. Nevertheless, the difference between the average values of the young and old plantations was significantly different. The findings are similar for middle-aged and old plantation trees. While the 22-year-old Újrónafő 11G trees exhibited the highest SWV values of 4276.2 m/s, the 29-year-old Kapuvár 35A logs had the lowest average SWV values of 4139.4 m/s (*Table 2*).

The density results of the samples originating from the test logs indicated that Pannónia poplar sapwood might differ significantly from its heartwood, which could influence its usage as structural timber. Based on the laboratory test results, the highest dynamic MOE can be expected in Újrónafő 11G plantation, which has the highest sapwood and the highest heartwood density values (*Table 3* and *Table 4*). The higher dynamic MOE means better raw material for structural uses (*Table 5*); therefore, we can forecast that Újrónafő 11G may be the most suitable among the tested sites for producing poplar lamellas for load-bearing, glued laminated timber.

Acknowledgements: The authors are grateful to the National Research, Development and Innovation Office Hungary (NKFIH) for the financial support in frame of the project OTKA K116216 “Complex analysis of the physico-mechanical and surface-physical properties of wood with low density”.

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https://doi.org/10.37045/aslh-2022-0009 *Acta Silv. Lign. Hung., Vol. 18, Nr. 2 (2022) 129–150*

Student Knowledge and Attitudes Towards Wood and the Use of Wood as a Raw Material

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Abstract – There is much uncertainty about the attitude toward raw wood material use: Is the wide-range use of unprocessed wood recommended or not? In our statistically representative questionnaire survey completed in Győr-Moson-County schools in Hungary, we aimed to discover which components of attitude determine the willingness of future energy users to use wood. A novelty of our study is that we investigated three components of attitude in the context of wood use, i.e., the cognitive, the affective, and the conative components. We used Decision Trees in statistics, hitherto unemployed in wood-related environmental education research, to predict the willingness to use the raw wood material. Our study is relevant to sustainable development and climate protection. Our results revealed that only one-third of participants provided an affirmative response to the question of whether they would use raw wood material. Furthermore, we found that the affective component of attitude is a stronger predictor than the cognitive component, with the conative component not being a predictor. In light of these results, we recommend popularizing forest programs since the attitude-changing effect of forest programs has been confirmed.

forest programs / experiential pedagogy / tree-related attitude / Decison Tree Analysis / future use of wood / Győr-Moson-Sopron County (Hungary)

Kivonat – A tanulók tudása és attitűdje a fához és a fa alapanyagként való felhasználásához. Nagy a bizonytalanság a faalapanyag használathoz való hozzáállás tekintetében: a széles körű faalapanyag használata ajánlott vagy sem? Statisztikailag reprezentatív kérdőíves felmérést végeztünk Magyarország egy megyéjének iskoláiban és arra voltunk kíváncsiak, hogy az attitűd mely összetevői határozzák meg a fahasználati hajlandóságot, a jövő energiahasználói körében. Vizsgálatunk újdonsága, hogy az attitűd három összetevőjét elemeztük a fahasznál at kontextusában, azaz a kognitív, az affektív és a konatív komponenst. A fával kapcsolatos környezeti nevelés-kutatásban eddig a Döntési fák statisztikai modelljét nem használták a fa alapanyag felhasználási hajlandóság előrejelzésére. Így tanulmányunk a fenntartható fejlődés és klímavédelem szempontjából releváns. Eredményeink azt mutatták, hogy a résztvevők mindössze 1/3-a válaszolt igenlően, arra a kérdésre, hogy fa alapanyagot használna. Továbbá azt az eredményt kaptuk, hogy az attitűd affektív komponense erősebben jósol, mint a kognitív, és a konatív komponens nem prediktor. Ezen eredmények tükrében javaslatokat teszünk az erdészeti programok népszerüsítésére, mivel azok szemléletmódosító hatása bebizonyosodott.

erdei programok / élménypedagógia / fához kapcsolódó attitűd / döntési fa / jövőbeli fahasználat / Győr-Moson-Sopron Megye (Magyarország)

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1 INTRODUCTION

The present study investigates the following research question: What attitudes do children show towards the use of raw wood material? To obtain quantitative data on the issue, we conducted a statistically representative questionnaire survey in Győr-Moson-Sopron County in Hungary. The present study explored the uncertainty concerning the use of wood in every society. For example, Stout et al. (2020) demonstrate that the current generation does not possess solid knowledge of the wood products industry. Moreover, they also identify deficiencies in the knowledge of basic concepts. In the same vein, Polzin – Bowyer (1999) also observed great uncertainty concerning university students' knowledge of forests and wood products. They found that student knowledge of forests and wood products is incomplete and based on significant and all-encompassing misunderstandings.

Outdoor environmental education is one method to fill these knowledge gaps. Prokop et al. (2007) found a significant and positive increase in the attitudes of Slovak students toward biology three days after a field trip. Qu et al. (2011) tested Chinese university student knowledge and attitudes about forest bio-energy in China. They found that students had a positive attitude towards renewable energy in general but a slightly less positive attitude towards forest bio-energy, further highlighting the uncertainty in attitudes about forests and the theme of wood in the context of renewable energies. Qu et al. (2011) concluded that knowledge dissemination via different sources (e.g., teaching, Internet or other media channels) is a significant aspect of energy issues. We wanted to investigate this line of research by examining two more aspects of attitude towards trees and the use of wood in addition to the cognitive aspect: the affective and the conative aspects (see later).

Foreign research results demonstrate that using wood as a raw material positively affects psychological, physical, and mental health: trees in the physical space activate neurological, psychological and physiological responses (Jarmusch 2003, Rice 2004). Furthermore, the use of wood as a building material in schools has a positive effect on student performance and stress tolerance (Elias 1989, Kelz et al. 2011). We focused on extracurricular forest programs organized by schools to obtain data on whether these programs exert a demonstrable effect on the younger generation concerning the use of wood. Our main research aim was to assess existing student knowledge about wood, its use, and attitudes related to wood to determine the factors explaining and predicting the wood use among our participants. The second research aim was to obtain information to assess the conscious willingness to use raw wood material as adults. The third aim was to acquire data on whether out-of-school wood-related activities – such as forest programs, field trips, forest-study tours, tree planting programs, or "campfire" programs in forest clearings – influence attitudes towards wood and the use of raw wood materials.

In line with Prokop et al. (2007), we hypothesized that students participating in such school-related extracurricular activities or wood-related programs exhibit higher scores on the cognitive, affective, and conative components of environmental attitudes towards wood than those who did not participate in such activities. However, due to the explanatory nature of our study, we postulated no hypotheses regarding the importance/weight of the three aspects of attitude.

2 FOREST PROGRAMS

Forest programs are of key importance to our research because forests play an undeniable role in public welfare (Országgyűlés Hivatala 2016). Several studies have been conducted on forest school programs, educational paths (educational trails, nature trails) and their positive effects and changes in environmental attitudes, demonstrating the positive effects these programs have on attitude (e.g., Lampert 2008; Lehoczky 1999, Leskó 2017; Kövecsesné Gősy 2009). Unfortunately, forest school programs are unavailable to many schools and funding opportunities are also limited (Leskó 2017). Taking these facts as a starting point, we explore the effects of shorter-term programs that require no funding. Students participating in public education participate in forest programs several times a year as part of the school curriculum. Therefore, forests can become a new educational site, a novel educational institution (Lohri – Schwyter 2002). Well-organized excursions, forest visits, walks, and forest school activities provide a lasting experience for children, with experience being an emotional phenomenon that affects the child due to its strong emotional charge. Thus, such interventions are meaningful educational tools (Hartl 2008). Moreover, forest programs aid the development of critical and independent thinking by promoting the development of environmentally conscious behavior and environmental responsibility via the formation of attitudes, values, emotions, and knowledge expansion about the environment, society, and culture. For example, by exploring the surrounding mountains and educational trails, students can develop orientation and map-using skills, physical and motor skills, and coordination.

During these programs, a forester can aid teachers through their knowledge of environmental problems. Foresters can also expand environmental knowledge in students (Lohri – Schwyter 2002, Kováts-Németh 2011). To the best of our knowledge, no research has been conducted on the use of wood in connection to whether extracurricular forest programs organized by schools (walks, excursions, “campfire” programs in the forest) have an impact on current primary and secondary school students. We focused exclusively on wood use because the topic has become highly relevant throughout the world due to the energy crisis. This distinguishes it from other themes related to school forest programs such as handcrafts, preserving cultural-historical traditions, field study, or health preservation. A second motivation is the uncertainty surrounding using wood as an energy source and wood use in general.

We chose the primary and secondary student age groups because these students will eventually become future energy users. The topic of the present paper is important from several aspects. On the one hand, from the forest management perspective, our research provides information on the willingness of the next generation to use raw wood material. From the point of view of climate protection, the carbon sequestration role of raw wood materials is significant, which is also relevant to future renewable energy sources. Our research is also meaningful for environmental education (including adult environmental education) and exploring new ways and opportunities to promote sustainable development through education. In the following, we elaborate on these aspects and present our statistically representative study. Subsequently, we discuss the results, draw conclusions, and provide suggestions for out-of-school forest program opportunities with a specific focus wood use.

The present topic is relevant to forest management due to the misinformation the media and nature conservationists tend to convey about wood (e.g. Kováts-Németh 2010). Citizens also misjudge wood material use and tend to view the work of foresters negatively (Gregory 1996, Kováts-Németh 2010, Folcz 2013, Lomniczi 2018). For example, wood as an industrial raw material is a missing natural resource in public thought (Hartl 2008). Therefore, one of the uncertainties in recent decades is the growing concern about global deforestation and forest degradation (Paquette – Messier 2010, Donato et al. 2011, McNeill 2011). The deteriorating state of forests, the accelerating growth of the global population, and the increasing penetration of nature also affect the use of raw wood material (e.g., Kováts-Németh 2010). Concerns about wood extracts and wood substitute use are increasing, resulting in a trade-off between wood products and wood substitutes. Industries replacing wood products with other materials also believe their products have environmental benefits, adding to the mentioned uncertainty (Durugy 1996, Kováts-Németh 2010).

Scientific evidence suggests that wood product use in construction and everyday life positively affects the climate (Az Európai Unió Hivatalos Lapja 2015). Wood use in furniture and building materials, together with its storage capacity, leads to decades- or centuries-long atmospheric carbon sequestration (Antal 2014, Carle et al. 2002, IPCC 2000, National Forest Strategy 2016-2030, Rumpf 2011, The Elias Review 2008).

According to the Hungarian National Forest Strategy for 2016-2030 (National Forest Strategy 2016-2030), the expanding and multi-stage sustainable use of harvested timber in the timber industry will help reduce climate change effects. Moreover, wood products should be used for energy recovery at the end of their life cycle following circular economy principles. Brechin (2003) reviews concerns about global warming on several continents and examines the effects of burning fossil fuels. The countries he studied are uncertain about global climate change (Brechin 2003). The natural sciences have demonstrated a clear link between empirical evidence on atmospheric gas composition and terrestrial climate change (e.g., CIFOR 2013; WRI 2008). The short-term enrichment of greenhouse gases such as carbon dioxide, methane, and nitrous oxide will lead to changes in the heat balance of the atmosphere, which in turn will be reflected in climate change. The amount of carbon stored in forests in the form of wood cannot be neglected, as forests are the most efficient carbon dioxide (CO_2) reservoirs in the Earth’s atmosphere after plankton stocks in oceans. Therefore, increasing and preserving forest areas contributes much to maintaining global carbon turnover.

The Official Journal of the European Union contains the European Economic and Social Committee's (EESC) opinion on the contribution of the forest-based sector to carbon balance. The opinion concludes and makes recommendations for increasing the wood supply and the sustainable use of wood as a raw material. The EESC urges Member States to develop national action plans to increase wood in buildings and green infrastructure. In sum, the EESC promotes a culture of wood use in buildings, thereby reducing CO_2 emissions.

The role of forests and trees in the next century may be greater than ever before, with forests being the most complex natural (ecological) system on Earth and one of the basic supporters of human life. Forests play a key role in the protection of soil, the atmosphere, and the climate. As a renewable natural resource, forests produce raw materials, energy, and food in addition to the continuous improvement of the environment (Act XXXVII of 2009 on the protection of forests).

3 ENVIRONMENTAL EDUCATION AND ENVIRONMENTAL ATTITUDES

The international professional community believes education should create values for a sustainable future and promote behavior and lifestyles (Cseri ed. 2003, p. 14; Larson et al. 2011, Leeming et al. 1995). The National Core Curriculum in Hungary has been revised several times and now includes environmental education, sustainability and environmental awareness as priority areas for development (National Core Curriculum 2021). In line with the National Core Curriculum, Hungarian researchers have examined the importance of environmental education. They have concluded that environmental education can help children develop habits and behaviors that form the basis of a balanced relationship with their environment in their adult lives (Ádam 2007). As a result, environmental education and sustainability have also gained a new approach and content in Hungary. According to Havas (2001), environmental education includes values that serve as sustainability prerequisites, making the relationship between the two concepts indisputable. In this vein, Ádam and Boldis also underscore that the balance between man and nature should be the goal of environmental education (Ádam – Boldis without years).

The link between sustainability and environmental education raises the question of how environmental education can be improved in the context of wood and trees. Studies to determine the positive influencing of environmental attitudes are also underway. For example, Halász et al. (1979) and Paksi (2013) suggest many ways to achieve states of mental and neural calmness through experience that has a dynamic or controlling effect on an individual's response to all objects and situations to which the attitude applies. Researchers distinguish three domains of environmental attitudes: the cognitive domain (component) referring to knowledge in general, the affective domain (component) encompassing emotions and the conative domain (component) referring to actions and behavior in the present or the future (Allport 1935, Maio – Haddock 2010). Among the factors influencing the development of effective environmental attitudes, the direct environment, learning environments, the impact of human interventions, and the physical environment of schools have been studied in a domestic and international research context (Izadpanahi et al. 2015). However, a sophisticated analysis of these three attitude domains in has not been completed the context of wood and trees. The present paper provides such an analysis and investigates these three attitudes separately to determine whether they explain and predict the willingness of future wood use.

In addition to institutional education, the significant role that family plays in the environmental education context is worth noting. Molnár (2009) shows that promoting an environmentally conscious lifestyle and developing environmental attitudes are crucial mediums for environmental education in families with children. Besides family, the living environment also plays a habit-forming role in environmental education. Konyha (2011) examined the environmental attitudes of high school students, their attitudes toward environmental issues, and differences in environmental attitudes across places of residence. Konyha (2011) showed that students living closer to nature in the countryside have more positive environmental attitudes than those living in cities. This finding is also in line with Conell et al. (1999), who studied the environmental attitudes of students from 15 countries in different places of residence. Konyha (2011), who also analyzed the three domains of environmental attitudes, and found the emotional aspect to be stronger than the behavioral aspect. This finding is significant to our research question. Further, Konyha (2011) found that younger students displayed more positive environmental attitudes. Moreover, children with a positive attitude tended to come from families emphasizing environmental protection (Konyha 2011). To support the thesis that family is a vital factor in environmental education, Rickinson (2001) reviewed more than 100 empirical studies, scholarly articles, and books that presented findings and gaps in the effectiveness of environmental education. The age groups studied were primary and secondary school students. Several studies reviewed by Rickinson acknowledge the family's role as a source of environmental information: after television and school, it is the next most important source of information for young people. However, research cannot unequivocally confirm whether attitudes determine action or behavior; conversely, whether behavior influences attitudes (Formádi 2013). Taking the attitude theory by Atkinson and colleagues, Formádi (2013) argues that the influence of attitudes on behavior and action is stronger when the cognitive and affective components are strong, consistent, and experiential. Formádi (2013) further suggests that specific attitudes towards a specific object or phenomenon are more effective. In the following, we present our study examining the relationships between forest programs and the willingness to use raw wood material. This study and the statistical analysis are explorative in that we wanted to discover the driving factors for the subjective importance of wood.

4 MATERIALS AND METHODS

We conducted a county-wide questionnaire in Hungary to investigate the attitudes of the upcoming generation by surveying the age groups of the 7th year of primary school and the 11th year of secondary school. The survey was conducted in Győr-Moson-Sopron County in Hungary during April, May, and June of the 2021 school year. A decisive factor in the county selection was the high tree cover density in the region, which opens up possibilities for tourist- and educational trails, visitor centers, and forest schools in the surrounding forests. A second reason was that this is the only county in Hungary offering a vocational training program, i.e., professional training in forestry and the wood industry.

We piloted the survey questions on ten students before administering the questionnaire. The ten participants were selected randomly, and they were debriefed after filling in the questionnaire. The questions were adjusted to the level of the age groups under investigation and the questionnaire length. Informed parental consent was collected before completing the survey. The questionnaires were administered online using Google Docs during regular school classes with no time limit for filling in the questionnaire. Neither the teachers nor the participants were aware of the study hypotheses. The raw data supporting the study findings are accessible in the Data Availability section at the end of the manuscript.

Our questionnaire was completed by 230 male and 200 female students. The youngest respondent was 10 years old; the oldest was 20 years old (mean age=14.56 years, SD=2.18 years). The total number of 430 participants, and the relevant sociodemographic variables, were counterbalanced to make the county-wide questionnaire survey statistically representative of the county. These relevant variables –submitted to stratification weighting – were gender, age, school type, and settlement size. Our sample is hence a proportional reflection of the specific characteristics in the target population, i.e., Győr-Moson-Sopron County. Based on the data from the Central Statistical Office in Hungary, abbreviated as KSH in Hungary, in Győr-Moson-Sopron County, there were 33,996 pupils enrolled in primary schools and 7,507 enrolled in secondary schools in 2014 (KSH; Központi Statisztikai Hivatal 2015, p. 12). The sample size calculation changes little for populations larger than 20,000[†] (Daniel 1999); therefore, we used 2014 data. To be statistically representative according to the formula for representativeness calculation – a target population size of around 41,500 students, with a margin error of 5%, and a confidence interval (*CI*) of 95% – the present study required 381 participants (Daniel 1999). Given the target sample size of 41,500 and the actual number of 430 respondents, the margin error decreased to 4.7% [95% *CI*]. This margin error indicates a 95% probability that the target population in this county would pick a value on any item, with the value lying within the interval of +/- 4.7%. Furthermore, this sample size is in line with other studies in the field: Qu et al. (2011) tested 441 students using a questionnaire study on forest bio-energy in China.

The questionnaire contained 49 questions (items) comprising categorical variables and a few ordinal variables (see *Table 4* and *Appendix*). After the sociodemographic variables in the questionnaire, questions followed related to respondent habits in school and family, traditions, feelings, and the willingness to use wood in the future. The questions were not randomized or pseudo-randomized across participants because we expected no order effects usually associated with other types of questionnaire studies. Fatigue could be such an order effect (e.g., respondent attention may have slipped towards the end of the questionnaire) or the tendency of some questions to affect response behavior by appearing later in the questionnaire. In the debriefings, participants reported no inconsistencies in the questionnaire. When recruiting respondents, we ensured that we achieved a proportion of primary and secondary school students representative of the county (see *Table 1*).

[†] For an online sample size calculator of statistical representativeness, see https://www.checkmarket.com/sample-size-calculator/ or https://www.qualtrics.com/de/erlebnismanagement/marktforschung/stichprobenrechner/

Table 1. Types of schools surveyed

	Frequency	Percentage
Primary school	230	53.5
Four-year grammar school	20	4.7
Six-year grammar school	15	3.5
Eight-year grammar school	42	9.8
Vocational secondary school	123	28.6
Total	430	100.0

We included differently sized settlements in the county for the sample proportionally. We distinguished three settlement types in line with the definitions provided in a Hungarian geography textbook (Földrajz tankönyv 8. lecke: Települések Magyarországon [Geography textbook, lesson 8: Settlements in Hungary], 2022): village, town (town: 10-25 thousand inhabitants), and city (city: over 25,000 inhabitants). Table 2 illustrates the participant locations and where participants grew up to explore how many students grew up in the countryside close to nature until they were 12.

Table 2. Location of schools participating in the survey and information about where the participants in the survey grew up until the age of 12

	Type of location of students' schools		*Type of location of upbringing until the age of 12*	
	Frequency	Percentage	Frequency	Percentage
Village	59	13.7	148	34.4
Town (town: 10-25 thousand inhabitants, e.g., Csorna, Kapuvár)	104	24.2	86	20.0
City (city: over 25 thousand inhabitants, e.g., Sopron, Győr)	267	62.1	196	45.6
Total	430	100.0	430	100.0

5 STATISTICAL ANALYSES

For the statistical analyses, we used the RStudio 1.1.442 (RStudio Team 2020) built on the R platform (R Development Core Team 2021, version 3.5.1). First, two independent raters performed a plausibility check to screen for outliers, such as respondents who completed the questionnaire randomly. The raters identified no such respondents. Following this, we computed summary statistics on the data to describe central tendency (mean, median, minimum, maximum, range, and standard deviation). There were two variable types in our dataset: nominal variables and ordinal variables, the latter measured on a 5-point Likert scale. With ordinal variables, we adopted the Hungarian grading system.

The main goal of the inferential statistical analysis, using a high number of potential explanatory variables, was to explain why participants find wood important (see variable “Importance of Wood”). It should be noted that the outcome variable “Importance of Wood” is an ordinal variable representing a continuum, entailing that a value on this variable can only be interpreted in reference to another value. Another implication of the ordinal nature of the outcome variable is that importance is a continuum. To operationalize the subjective importance of wood, we accept the values of 4 or 5 (indicating subjective importance on a scale of 1-5).

To address concerns about multicollinearity and non-linearity between dependent and independent variables, which are usually associated with multiple regression analyses, we employed the method of Conditional Inference Trees (Hothorn et al. 2006) to investigate which independent variables can account for the outcome variable "Importance of Wood". In statistics, multicollinearity is a phenomenon in which one independent variable can be linearly predicted from the others. Conditional Inference Trees can be used for a broad variety of variable types, such as nominal or ordinal response variables (Levshina 2015). Another reason to employ Conditional Inference Trees was to examine the whole variable space of eight potential explanatory variables in its entirety rather than separately as in the case of other traditional statistical procedures. The conditional inference model is flexible and, most importantly, generalizable (Hothorn et al. 2006).

For demonstrations of the use of Conditional Inference Trees in, for instance, the domain of linguistics, see e.g., Tagliamonte – Baayen (2012), Levshina (2015), Hentschel et al. (2019), or Fekete (2021). Conditional Inference Trees are essentially non-parametric regression models visualized as decision trees and serve as an alternative to multiple regression analyses in the presence of many potential predictor variables and the case of multicollinearity (Levshina 2015). With eight variables, we assumed potential multicollinearity.

Conditional Inference Trees employ an algorithm of recursive binary partitioning and split the dataset into partitioning variables that show an association with the outcome variable. The splitting process terminates when pre-defined stopping criteria are met. Hothorn et al. (2006) describe the methods of Conditional Inference Trees in detail. Decision trees in statistics are structures comprising so-called nodes and branches, starting at a single root node at the top of the decision tree and ending in terminal nodes (or leaves). At each node (or level), a single independent variable is considered for splitting the data into two partitions. The higher the variable in the decision tree hierarchy, the more important the variable, with the highest-level variable being the most important. Conditional Inference Trees were implemented with the party R package using the *ctree* function (Hothorn et al. 2006).

For the Conditional Inference Tree analysis, we entered the following eight independent variables as potential predictors of the outcome variable "Importance of Wood" (for all the factor variables in the study, see Table A in the Appendix). Table 3 illustrates the questions in the survey with the aspects of attitude.

Table 3. The questions related to the three components of attitude (cognitive, affective and conative components of attitude)

	Component of attitude
If the participant has ever taken part in a program where some old wood-related profession was shown	cognitive
If the participant has ever taken part in a school program or school camp related to wood	
If the participant has ever attended a "campfire" program	
"sadness-scale": "How sad would you feel if a wood-related tradition got lost?"	affective
Later, when the participant is an adult, does (s)he plan to plant a tree?	conative

We restricted the number of variables to this set of five items because the three components of attitude were operationalized via these variables, and we wanted to test only these aspects of attitude. All these variables are nominal variables except for "How sad would you feel if a wood-related tradition got lost?" and the "Current living environment?". The outcome variable "Importance of Wood" is also ordinal.

In the Conditional Inference Tree analyses, the raw data are submitted to the analyses, i.e., participant-level data, and not the aggregated data such as percentages, averages, medians, etc. We built a three-level tree structure to avoid so-called pathological splits associated with more levels (four or more). A pathological split would be a terminal node with very few participants or responses. Such a pathological split should be avoided for reasons of generalizability, i.e., the model might be over-fitted.

Importantly, we did not perform model-validation (cross-validation) on the data to assess the accuracy of the model because when using "mincriterion=0.95" in the model, no cross-validation is needed: "This statistical approach ensures that the right sized tree is grown and no form of pruning or cross-validation or whatsoever is needed." (Hothorn et al. 2021, p. 9)

6 RESULTS

Altogether 430 respondents filled in the questionnaire. *Table A* in the Appendix lists the results of all the factor variables in the dataset. *Table 4* contains the summary analysis of all the ordinal variables in the dataset.

Table 4. A summary analysis of all the ordinal variables in the dataset

The ordinal variables in the questionnaire	n	Mean	SD	Median
How sad would you feel if you saw a sick or dead tree?	430	2.98	1.20	3
How sad would you feel if a wooden tool broke?	430	3.27	1.25	3
How delighted do you feel if you see an old wooden object?	416	3.26	1.29	3
How important is it where people lived before?	430	3.38	1.17	3
How beautiful do find a wooden farmhouse?	430	3.9	1.11	4
How likely would you participate in a wood-related program?	314	3.25	1.43	3
Have you ever been to a program where old wood crafts were shown to you?	330	3.35	1.36	3
How sad would you feel if you missed a program with campfire?	394	3.59	1.33	4
How sad would you feel if a wood-related tradition was lost?	430	2.78	1.37	3
How important do you think that we should use much wood nowadays too?	430	3.48	1.10	3

The number of responses are represented by "n". SD designates standard deviation of the mean. Min and Max refer to the observed Minimum and the observed Maximum value of the ordinal scale. Range is the span of the scale.

Table 4 shows that some ordinal variables have missing values reflecting unanswered items by the respondents because these items did not apply to a subset of respondents. For example, those who have never participated in a campfire could not answer the question as to whether they would feel sad about missing such an experience. Because Conditional Inference Trees can combat missing values (Levshina 2015), missingness does not pose a problem for the subsequent analysis.

Before moving on the analysis via Conditional Inference Trees, we would like to focus on the uncertainty among students regarding the use of wood. The responses of 430 primary and secondary school students who participated in the survey revealed that 37.7% (162 people) are influenced by the fact trees felled for use, i.e., they would not use wood because trees are felled. In contrast, 29.3% of the surveyed students (126 people) answered the question with "I don't know", while 33% (142 people) were unaffected by the use of wood, i.e., they would use wood despite it being cut down. Thus, our survey data support the uncertainty about the use of wood as a base material.

The following eight potential explanatory variables were entered in the conditional inference tree analysis: School_wood_programme (if the participant has ever taken part in a school program related to wood), Tree_planting_adult (if the participant plan to plant a tree as an adult), Wooden_craftsman_shown (if the participant has ever taken part in a program in which a craftsman using wood was shown), School_campfire_activity (if the participant has ever taken part in a "campfire" program organized by the school), Current_living_environment (the current living environment of the participant), Campfire_attended (if the participant has ever attended a "campfire" program), Wooden_tradition_currently (if there is an old wood-related tradition currently in the present location of participant), and Scale_wooden_trad_lost (How sad the participant would feel if a wood-related tradition was lost).

Figure 1 illustrates the Conditional Tree Analysis results explaining and predicting the ordinal outcome measure "Importance of Wood". Each significant explanatory variable is represented by an oval circle together with the Bonferroni-corrected p-value. Classification rules are represented by levels of the significant explanatory variables expressed in the form of if-then conditions. Classification starts at the top node (see *Figure 1*, node 1), which is the most important variable in predicting "Importance of Wood" (p<0.001). Classification proceeds by moving down the branches until the terminal nodes marked in green are reached (see *Figure 1*). The number of responses on the routes is represented by n, which adds up to the total number of observations of 430 (*Figure 1*).

Node 1 is "Scale_wooden_trad_lost" (How sad would you feel if a wood-related tradition was lost?) proved to be the most important variable explaining and predicting the importance of wood, portioning the data into two sets (see the two routes in Figure 1): data on the scale of the variable "Scale_wooden_trad_lost" which were either 4 or 5 or lower than 4 (see the left and the right branches, respectively). We operationalize "important" on the variable "Importance of Wood" as a value of at least 4 on a scale of 1-5, whereby 5 means the participant finds wood very important. A cohort of 73 participants from 430 children scored a mean of 4.205 (see Figure 1, the leftmost green rectangle at the bottom). The most important variable ("Scale_wooden_trad_lost") reflects the *affective* component of attitude in line with Konyha (2011), who also found that the emotional aspect of environmental attitudes is stronger than the behavioral one. From a pedagogical point of view, this result demonstrates the need for strengthening the affective aspect of wood in environmental education in family, institutional, and out-of-school settings. Specifically, this result shows that conveying information on tradition-related wood is of utmost importance in environmental education.

If we follow the first route (values of 4 or 5 on the scale), then the next variable that splits the data into two is "School_wood_programme" (If the participant has ever taken part in a school program or school camp related to wood). This variable reflects the *cognitive* component of attitude, demonstrating the need for strengthening the knowledge aspect in environmental education both in family, institutional, or out-of-school settings. This variable further partitions the dataset into two (either "yes" or "no"). The *conative* component of attitude did not appear in the decision tree model, indicating the superiority of the affective and cognitive components. Crucially, the rest of the routes (the four green rectangles) lead to mean values below 4, indicating mediocre or no interest in wood use. Figure 2 is the same representation as *Figure 1*, with the only difference being the distribution of responses on the outcome variable, which are indicated at the bottom of the figure (see nodes 3, 4, 7, 8, 9).

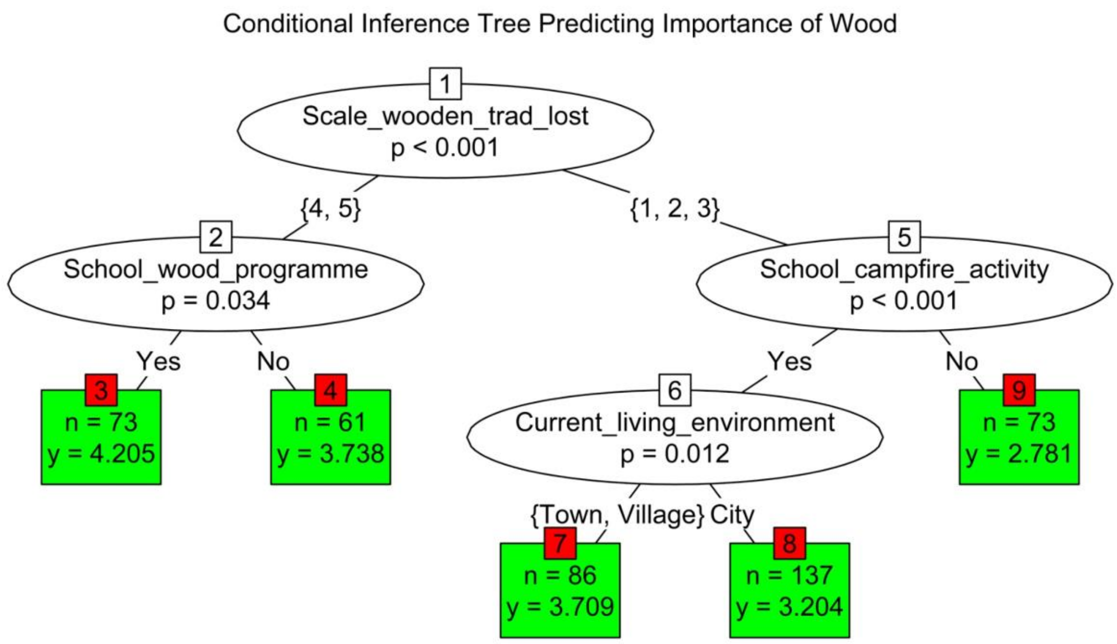

Figure 1. A Conditional Inference Tree structure explaining and predicting the ordinal type of outcome measure "Importance of Wood". Each significant explanatory variable is represented by an oval circle together with the Bonferroni-corrected p-value of the significance test. Classification rules are represented by levels of the explanatory variables expressed in the form of if-then conditions. Classification starts at the top node (root, node 1), which is the most important variable in predicting "Importance of Wood" (p<0.001). Classification proceeds by moving down the branches until we arrive at the terminal nodes marked in green. The number of responses on the routes is represented by "n".

Figure 2 illustrates the distribution of responses along the routes in the model. The leftmost route (Node 3) explains and predicts a high level of "Importance of Wood" in contrast to the rightmost route (Node 3). In both cases (Nodes 3 and 7), outliers can be observed (marked by an empty circle). Variables that do not appear in the decision tree structure are not relevant to explaining the outcome variable "Importance of Wood" in the presence of the variables in the model. In other words, including those variables would not improve classification accuracy significantly. However, this does not mean that the rest of the variables are not significantly associated with the outcome measure "Importance of Wood".

The following bullet points summarize the main insights:

- The *affective* component of attitude at the top of the tree model is of utmost importance in environmental education related to wood (<u>emotions about traditions</u>)
- The *cognitive* component of attitude depicted in the oval circle numbered 2 is second-most important in explaining and predicting the subjective importance of wood (<u>participation in wood-related school programs</u>)
- The *conative* component of the attitude (if they plan to plant a tree later in adulthood) does not appear in the structure of the decision tree.

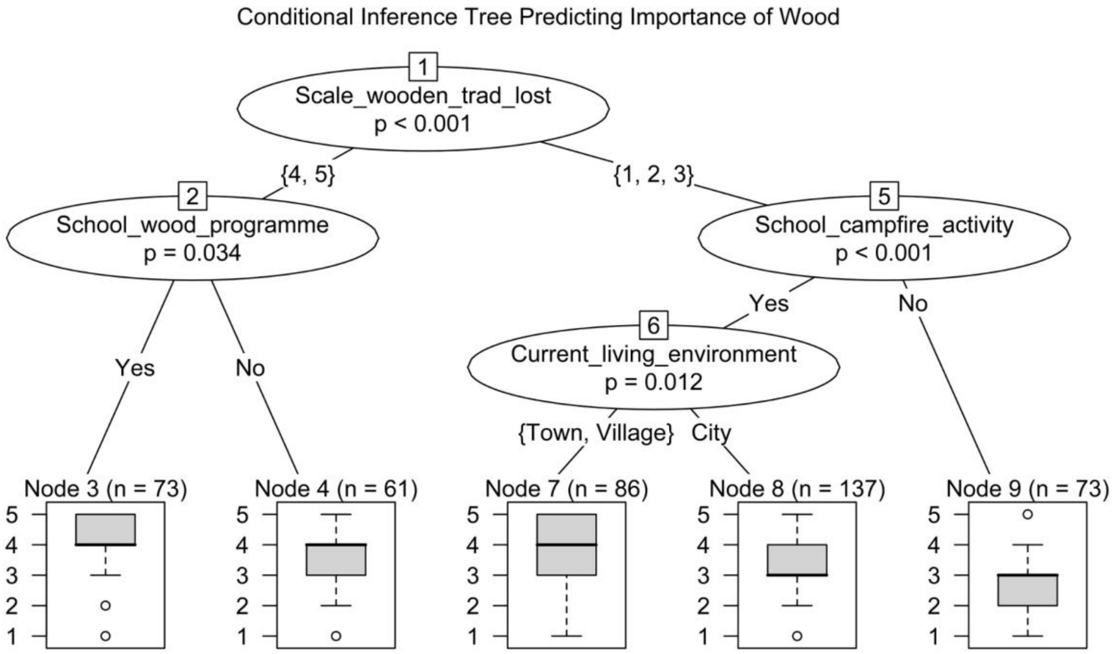

Figure 2. A Conditional Inference Tree structure explaining and predicting the outcome measure "Importance of Wood" with the distributions of responses at the terminal nodes. Oval circles in the representations at the terminal nodes designate outliers. Figure 2 is another representation of Figure 1: in Figure 2, the distribution of responses per node is illustrated.

7 DISCUSSION AND CONCLUSIONS

Let us begin by looking at the statistical representativeness of our survey. We surveyed just one county in Hungary, which raises a point of criticism about whether the results can be generalized to other counties. Considering the national standards in the curriculum across Hungarian counties, we do not expect any significant differences in the results relative to other Hungarian counties. Therefore, we argue that our survey findings can be generalized to the student population under investigation in Hungary. One potential study limitation is socio-economic status, which was not controlled. However, we argue that the effect of this potential confounder is reduced due to the relatively large sample size.

The "Decision Tree" model (Conditional Inference Tree) results showed that students who would regret the loss of a tree-related tradition and at the same time had participated in forest programs, trips, and events organized by their school, were likely to consciously use wood-based materials as adults. Our results revealed that the cognitive and affective domains of tree-related attitudes need to be strengthened in environmental education and the development of an environmentally conscious lifestyle. The finding that these two attitude components proved to be significant is in accord with Formádi (2013), who argues that the influence of attitudes on behavior and action is stronger when the cognitive and affective components are strong. The conative component did not prove to be a significant predictor of whether participants find wood important or not. We explain this finding by the nature of the conative component, namely that it refers to future action. The cognitive and affective domains have proven to be predictors in the model, as these two domains reflect the knowledge and emotional attitude acquired in the past and still exist in the present. However, the conative domain presupposes future actions, making this component an unstable predictor of behavior because the age of the interviewed students does not yet allow them to make independent decisions on all issues.

Regarding the hierarchy of the affective and the cognitive components, why the affective component ("emotion") is superior to the cognitive ("ratio") component requires explanation. The affective component is deeply rooted in our experiences, with first-hand experiences being more dominant in guiding behavior than our vicarious knowledge (the cognitive component). Formádi (2013) also underscores that the link between attitude and behavior is stronger when the attitude is based on direct experience. Note that direct experience is the basis of the affective component of attitude. Our findings also concur with Konyha (2011), who found that the emotional aspect is stronger than the behavioral aspect.

Concering the significant predictors in the decision tree, node 3 (Figure 1) proved to be the route that best describes those students for whom wood is important (Figure 1): in our sample, this is a small cohort of 73 students with an average of 4.205 on the importance scale (see node 3, Figure 1). These students have already participated in a school program related to wood (node 2 of Figure 1) and – at the same time – responded with 4 or 5 on the "sadness-scale" (node 1 of Figure 1). In contrast, an equal number of students (n=73) display the opposite pattern: these are students who did not take part in a school-organized campfire program and who – at the same time – gave a response of 1, 2 or 3 on the "sadness scale" (node 9 of Figure 1). This cohort does not find wood important at all, as shown by an average of 2.781 on the "importance scale" (Figure 1). The current living environment of the participants also proved to be a significant predictor of importance, with towns and villages showing a slight advantage relative to cities (node 6 of Figure 1). However, we believe that this result should be validated because the living environment in which the students grew up is more natural than their current environment. Figure 2 shows that the distributions do not vary (see terminal nodes in Figure 2), indicating that the predictive routes in the decision tree are comparable.

Our findings, in turn, illustrate that strengthening the first two components of attitude will promote the development of environmentally conscious behavior. Therefore, we recommend that teachers organize as many extracurricular forest programs as possible, following the recommendation by Qu et al. (2011). Importantly, a qualified specialist should organize such programs. For example, programs can be based on a forester's knowledge and professional knowledge. To strengthen the use of wood, we recommend promoting programs in which families with children can participate, in line with the research of Molnár (2009) and Rickinson (2001), who also confirmed that family is an important medium. To strengthen the use of wood as raw material, we suggest emphasizing affective attitudes, which can only be achieved if students spend as much time as possible in the forest, where they receive experience-based pedagogy. In the context of Konyha (2011), the difference between the environmental attitude of village and city children could be reduced, in our opinion, even though in our research the distribution according to residence did not influence the willingness to use wood material in the future. According to Kónya (2018), the effectiveness of environmental education requires data acquisition (for example, studies) and clear identification of students' existing knowledge, knowledge gaps, feelings, and their willingness to act in the future (Kónya 2018; Conell et al. 1999).

We consider it important to encourage and strengthen the widespread of wood-based materials in the context of our proposals for the further use of our research regarding wood and wood use. Deepening the relationship with wood and encouraging today's young generation to fall in love with it is essential for developing environmentally-friendly behavior. The future generation's attitude towards the environment and environmental protection depends on us, the older generation, so we have a responsibility in the educational process. In this educational process, families must also take an active role in cooperating with the school. The upcoming generation must be aware of global and local environmental problems to preserve and improve the quality of life. According to the Hungarian National Basic Curriculum, all young people should strive to know their environment, recognize existing problems, perform actions to protect and preserve their environment, and prevent environmental problems (Nemzeti Alaptanterv 2021). Finally, from a statistical perspective, we deem our research seminal in that we used the framework of conditional inference trees, hitherto unemployed in silviculture research. Suggestions for further statistical analyses based on the raw data can be found in Fekete and Kendöl (2022).

Acknowledgements: We are indebted to the study participants and the teachers at the schools.

Declaration of interest: We have no conflicts of interest to report. All relevant ethical guidelines have been followed as well as the ethical principles for research involving human subjects in accordance with the Declaration of Helsinki (World Medical Association 2013).

Data availability: The data that support the findings of this study are openly available in the Figshare repository at https://figshare.com/projects/Assessing_attitudes_towards_wood_in_the_context_of_family_habits_a_large-scale_quantitative_study_in_Hungary/132230. Researchers must give us credit in the form of a citation, should they use or refer to the research object uploaded. Owner of the dataset is Jutka Nmarné Kendöl. The original questionnaire can be found on Google Docs: https://docs.google.com/forms/d/1jvQspylELSzGJjyDhZLmtIXhDguosDf8qIKF_90H3dA/edit

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APPENDIX

The Appendix contains a summary analysis of all the factor variables in the study. The numbers represent the number of observations per level of the factor in question.

Table A. A summary analysis of all the factor variables in the dataset.

The factor variables in the questionnaire			
Gender			
	Boy	Girl	
	230	200	
Type of school the participant			
	Elementary school	High school	Secondary technical school
	230	77	123
The current living environment of the participant			
	City	Town	Village
	267	104	59
The environment the participant was raised in until the age of 12			
	City	Town	Village
	196	86	148
If there someone in the family who works with wood as a professional			
	No	Yes	
	321	109	
Whether the participant would like to deal with wood as a professional later in his/her life			
	I don't know	No	Yes
	116	250	64
Whether the family heat with wood in the household			
	I don't know	With coal	With district heating
	60	10	46
	With gas	With other heating resource	With wood
	164	20	130
Whether the participant watches movies or documentaries related to wood			
	No	Yes, alone	Yes, with my parents
	271	83	76
Whether the family of the participant have trees in their garden			
	No	Yes	
	65	365	

When there is a family event, such as the birth of a child or a wedding, do they plant a tree?			
	I don't know	No	Yes
	41	327	62
Whether the participant plans to plant a tree in adulthood			
	I don't know	No	Yes
	77	27	326
If there is a wooden tool or piece of furniture in the family			
	I don't know	None	Yes, a few years
	14	14	145
	Yes, a lot		
	257		
How the participant would replace a destroyed or ruined wooden object or tool			
	I would replace it with other materials	I would replace it with wood	I wouldn't replace it
	85	307	38
What the participant would do with a broken wooden tool			
	I would burn it	I would throw it out	I would try to recycle it
	116	65	249
If there is a wooden tool in the family of the participant			
	No	Yes	
	244	186	
If there is an old wooden object in the family inherited			
	I don't know	No	Yes
	160	67	189
If the participant would choose a wooden piece of furniture later as an adult			
	I don't know	No	Yes
	83	8	339
If the participant has ever seen an old farmhouse from wood which one can still live in, or which can be restored			
	No	Yes	
	85	345	
If the participant has ever lived in a wooden farmhouse			
	No	Yes	
	152	278	
If participant finds that a wooden farmhouse is environmentally friendly			

	I don't know	No	Yes
	169	115	146
If the participant would build a wooden farmhouse			
	I don't know	No	Yes
	114	162	154
If the participant has ever taken part in a school program or school camp related to wood			
	No	Yes	
	244	186	
If participant has taken part in such as program, would they do it again?			
	I don't know	No	Yes
	208	76	146
If the participant has ever taken part in a program where some old wood-related profession was shown			
	No	Yes	
	186	244	
If the participant would like to attend a wood-related workshop at school			
	I don't know	No	Yes
	137	183	110
If participant has ever taken part in a school activity where wood was involved or burnt			
	No	Yes	
	96	334	
If the participant has ever attended a campfire program			
	No	Yes	
	239	191	
If participant has ever seen a TV program in which wood or traditions related wood were themes			
	No	Yes	
	153	277	
In the current location of participant, is there an old wood-related tradition currently?			
	No	Yes	
	239	191	
If participant plans to celebrate wood-related traditions in adulthood			
	I don't know	No	Yes
	186	155	89
Deforesting effect: participant had to answer if he/she thinks that their use of wood is affected by the knowledge/fact that trees are cut			

	I don't know	No	Yes
	126	142	162

Table A illustrates the distribution of all ordinal variables in the dataset valid number of observations (*n*), mean, standard deviation of the mean (*SD*), median, minimum, maximum, and range.

https://doi.org/10.37045/aslh-2022-0010 *Acta Silv. Lign. Hung., Vol. 18, Nr. 2 (2022) 151–166*

Effects of Red Mud on Plant Growth in an Artificial Soil Mixture

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Abstract – Transforming economies towards the increased circular use of raw materials and keeping resource consumption within planetary boundaries is a major challenge. In our previous research, we utilized sewage sludge to produce artificial soil mixtures well-suited to the biological recultivation of degraded areas. The present study investigated how we can integrate red mud, often considered waste, into this circular management form. With red mud volume ratios of 15% and 30%, we experienced good germination and growth in Siberian elm (*Ulmus pumila* L.), white poplar (*Populus alba* L.), black locust (*Robinia pseudoacacia* L.) and the perennial multipurpose crop, Virginia mallow (*Sida hermaphrodita* L.). Our results indicate that it is worthwhile to scale up this cheap, economically and ecologically favourable combined waste recovery and mine reclamation technology and to expand its use to full-scale operation.

circular economy / waste utilization / mine recultivation

Kivonat – A vörös iszap hatása a növényi növekedésre mesterséges talajkeverékekben. Az emberiség egyik legnagyobb kihívása a jövőnk szempontjából, hogy gazdaságát a nyersanyagok fokozott körforgásos felhasználása felé alakítsa át, az erőforrás-felhasználást ’bolygóhatárokon’ belül tartva. Korábbi kutatásainkban olyan mesterséges talajkeverékeket sikerült előállítanunk, melyek szennyvíziszap hasznosításával kiválóan alkalmasak voltak degradált területek biológiai rekultivációjára. Most azt vizsgáltuk, hogyan tudjuk e körkörös gazdálkodási formába beilleszteni az egyébként hulladékként jelentkező vörösiszapot: 15% és 30%-os térfogat-arányú adagolása mellett jó megeredést és növekedést tapasztaltunk pusztaszil, nemesnyár, fehér akác fafajokkal és sida energianövénnyel. Eredményeink szerint érdemes ezt az olcsó, gazdaságilag és ökológiailag kedvező kombinált hulladékhasznosítási és bányahasznosítási technológiát működő üzleti környezetben tesztelni és alkalmazását teljes körű működésre növelni.

körforgásos gazdaság / hulladékgazdálkodás / bányarekultiváció

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1 INTRODUCTION

The ‘planetary boundaries’ approach sets scientifically-based limit values for resource use, above which the functioning of critical Earth-systems processes may permanently be disturbed (Steffen et al. 2015). The European Union has drafted an action plan to transform its economies towards significantly increasing the circular use of raw materials and keeping resource consumption within planetary boundaries (European Commission 2020).

On average, every ton of alumina results in 1.0–1.8 tons of red mud (Wang – Liu 2021). The annual production of this bauxite residue reaches approx. 175.5 million tons worldwide annually (>20 kg/head of the global population). Only 1–2% is recycled, leaving a global stock of over 4 billion tons (Liu et al. 2021). This inefficient resource exploitation has raised far less attention than the much-reported burst of a disposal dam in Hungary in 2010. In 2017, we entered into a cooperative venture with MAL Ltd., the main alumina producer in Hungary, with over a million cubic meters of red mud in its reservoirs. Our task was to tackle the challenge of changing the operations from a linear to a circular economy.

Pure aluminium does not occur naturally and has only been utilized in the past two centuries. Aluminium production requires bauxite, which is the product of natural soil formation (intense weathering), predominantly formed by the residual enrichment of Fe and Al, comparable to tropical-subtropical lateritization. Bauxite is a typical geological formation in the Transdanubian Central Mountains of Hungary, and it is also one of Hungary’s most valuable mineral raw materials (Fülöp 1969; Schellmann 1994).

The Bayer process, which adds high amounts of sodium hydroxide to the finely-milled basic material, is the most important industrial process used to extract aluminium from bauxite ore. Consequently, red mud, the main solid by-product, has very fine particle size distribution and a pH value of around 12.5. Red mud consists mainly of hydrated forms of Fe_2O_3, Al_2O_3, Na_2O, SiO_2 and TiO_2, and small quantities of trace elements like K, P, Mn, Mg, Cu, Zn, Pb, Cr, V, Ni, Ba, Sr, Zr, Y, Sc, G and other rare earth elements (Luidold – Antrekowitsch 2011).

Due to its composition, red mud must be treated as hazardous waste; however, its many valuable components have inspired numerous technological developments to permit utilization. To date, no operable and cost-effective large-scale solutions have been developed. The options vary, ranging from soil improvement to metallurgical processing: construction utilization, chemical use, environmental protection, agriculture and metallurgy (Lengyel – Lakatos 2011).

Previous studies examining the possibility of red mud utilization in the recultivation of infertile land in abandoned mines (Feigl 2011, Gray et al. 2006) have concluded that using hazardous wastes for chemical stabilization can be safe and beneficial because the additives have the potential to reduce the extractable and plant available heavy metal content and toxicity of soils. These wastes can be considered low-cost and long-lasting additives that can be used in artificial soil mixtures in certain quantities without harmful consequences. Furthermore, red mud has also been touted as an effective adsorbent for water pollution control due to its significant adsorption potential and ability to remove toxic pollutants from wastewater (Bhatnagar 2011).

Our investigations on the use of red mud were linked to the in-situ production of a soil substitute based on a recent invention (Heil et al. 2019) related to the utilization of sludge from the treatment of urban wastewater and other non-hazardous waste suitable for biological treatment, in combination with recultivating degraded lands and generating green energy on this new artificial surface. The proven advantage of this technology is its ability to protect valuable organic material from rapid decomposition through the formation of organo-mineral complexes and the degradation stabilization of organic matter (Lachmann 2018).

Using the addition of red mud in different proportions (based on Berta et al. 2021), the present study investigated the physical and chemical properties of an artificial soil mixture made from quaternary clayey loess (Pleistocene), sewage sludge and other biological waste materials, monitoring their effects on the growth of three herbaceous and five woody plants in a pot experiment over two consecutive vegetation periods. We hypothesized that the appropriate addition of red mud to the above artificial soil mixture may create adequate growth conditions for some plant species, allowing them to utilize the large amounts of water and nutrients it contains. Over time, the initially high salinity of red mud is expected to decrease, which may positively affect plant growth.

2 MATERIALS AND METHODS

2.1 Recipe of the artificial soil mixtures used as pot substrate

Artificial soil mixtures were prepared in March 2019. *In situ* red mud from aluminium production (EWC 01 03 09) was sampled from Reservoir Nr. IX. of MAL Ltd., H-8400 Ajka, Gyártelep hrsz.: 598/15; 47°05’12.45” N, 17°30’07.08” E); the composition given by the producing company was described by Pekler (2020). Loess was taken from the Székesfehérvár II. clay mine, the recultivation of which was performed by Fehérvári Téglaipari Kft (47°13’21.66” N, 18°24’50.97” E) (*Figure* 1). Sewage sludge (EWC 19 08 05) originated from the municipal wastewater treatment facility of Fejérvíz Ltd., which treats ca. 12 million m^3 of wastewater yearly (H-8000 Székesfehérvár, Bakony u. 10., hrsz.: 020023/5-6; 47°11’05.57” N, 18°23’17.66” E).

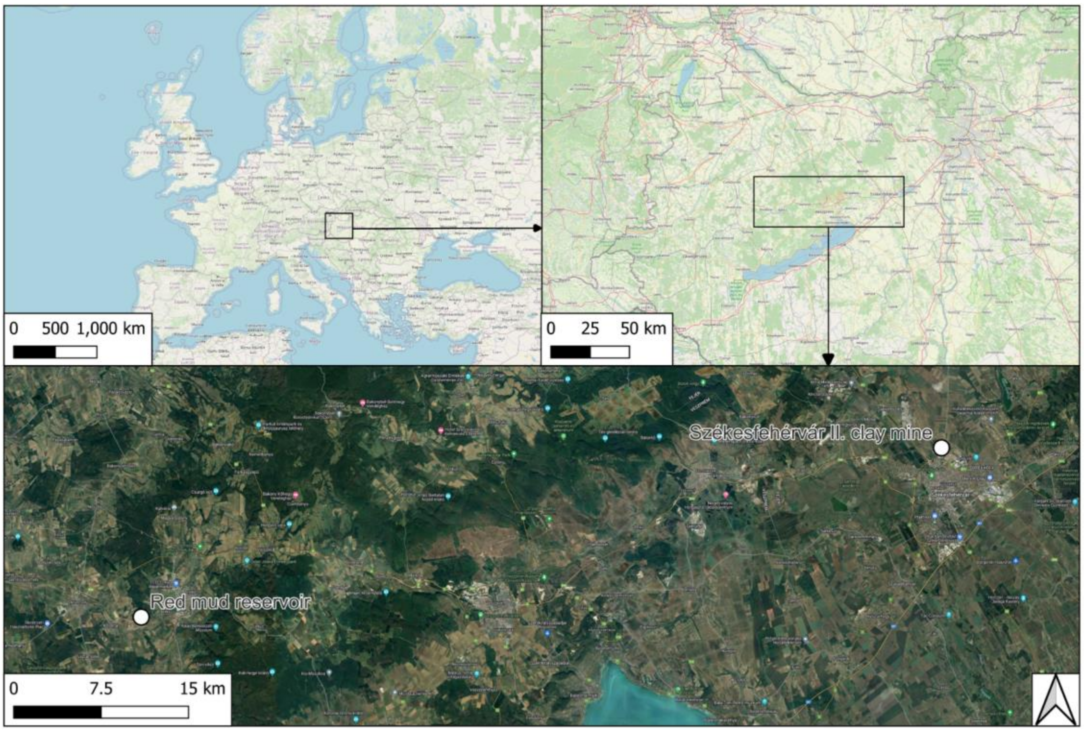

Figure 1. The place of origin of the red mud and the location of the experimental area

We established a long-term batch pot experiment in open-air conditions on the recultivated surface of the Székesfehérvár II. clay mine. The site is in the warm temperate forest zone (mean annual temperature 9.8–10.2°C) and is dominated by deciduous broadleaf tree species. The elevation is 135 m. The mean annual precipitation is about 530–560 mm, of which ca. 310-330 mm falls in the growing season. According to the Hungarian forest climate classification, the area’s climate is suitable for sessile oak / Turkey oak because the 30-year (1961–2010) average of the Forestry Aridity Index (FAI) interpolated to the area is between 6.00–7.25 (Führer 2017), indicating rather dry conditions for trees.

Two differing red mud soil mixtures were prepared with the same artificial soil mixture as basic material, as described in the patent of Heil et al. (2019), and seven-fold repetitions were prepared for each condition and plant species. Based on previous literature data, we chose a 15% red mud addition by volume (RM15) as a likely non-harmful ratio for plant cultivation. The 30% addition (RM30) was expected to be an extreme scenario with potential negative effects on vegetation used in recultivation. We mixed the additives thoroughly with a shovel and performed the planting directly after we produced the soil mixture.

The open-air pot experiments were conducted in 9 L plastic pots, weighing in equal amounts of the different soil mixtures to ensure comparable conditions for root development. The moisture content was set to reach field capacity: this was the water content of the soil mixture three days after irrigation, as gravity had removed the water surplus. Rainwater collected in tanks was used for irrigation. The experiments were conducted in the growing seasons (from March to September) over two consecutive years, 2019 and 2020.

2.2 Plant species used for comparison

Three herbaceous and five woody plant species were used for the tests: giant reed (*Arundo donax* L.) was set with two rhizomes per pot, Virginia mallow (*Sida hermaphrodita* L.) and Jerusalem artichoke (*Helianthus tuberosus* L.) with two medium root tubers per pot. One bare-root field maple seedling (*Acer campestre* L.), pedunculate oak (*Quercus robur* L.), white poplar (*Populus alba* L.), Siberian elm (*Ulmus pumila* L.) and black locust (*Robinia pseudoacacia* L.) was planted per pot (*Figure 2*).

Seedlings were purchased from a forestry nursery in the nearby village of Moha (47°14’22.20” N, 18°20’44.89” E).

*Figure 2. Plants collected for final measurements in the second year of the pot experiment in Székesfehérvár. The black planting pots are: 22.5 cm * 22.5 cm at top, 18.0 cm * 18.0 cm at bottom, height 26 cm. Plant species from left to right: 1.) Quercus robur* L.; *2.) Ulmus pumila* L.; *3.) Acer campestre* L.; *4.) Populus alba* L.; *5.) Robinia pseudoacacia* L.; *6.) Sida hermaphrodita* L.; *7.) Arundo donax* L.

2.3 Soil analyses and measurement of plant parameters

By examining the artificial soil mixtures created in the experiment, we tried to propose the use of mine reclamation methods that could be applied to make degraded surfaces suitable for non-food crop production purposes. In this regard, soil is the main nutrient source for plants and supports growth in various ways. To assess the health of this medium, we investigated soil quality with detailed physical and chemical analyses and measured the main plant growth parameters grown in them.

The main soil parameters were pH(H_2O), H% (calculated from C_{org}%), total soluble salt content, $CaCO_3$ content, amounts of extractable plant available essential nutrients (P, K, N, Ca, Mg, S, Zn, Cu, Mn, Mg), according to the Hungarian standards (MSZ-08-0206-2 2.1, 2.2:1978; MSZ-08-0205-2: 1978; MSZ-08-0206-2: 1978; MSZ-08-0452: 1980; MSZ-20135:1999). This soil parameter range corresponds to Decree No. 4 of 2004 (I. 13.) FVM of the Hungarian Ministry of Agriculture and Rural Development, released to determine the minimal requirements of agricultural and environmental management, foreseen by national and EU legislation as necessary conditions to use rural development subsidies according to the National Rural Development Plan and financed by the European Agricultural Guidance and Guarantee Fund.

To determine the bulk density of the artificial soil mixtures, ten repetitions per treatment and plant species of 100 cm^3 samples were taken from the pots at the end of each year with 'Vér' soil-core sampling cylinders (100 cm^3 metal cylinder for undisturbed soil sampling).

We determined the following measurements. For herbaceous plants, the subsurface root mass, the aboveground biomass and the height of the plants, and for woody plants, the same parameters plus woody stem diameter at stem basis. We determined all of the above at the end of both growing seasons by breaking down the pots.

2.4 Data procession and statistical analyses

Statistical analyses were conducted with help of the StatSoft Statistica software, according to the following order: preparation of descriptive statistics; plotting the mean and confidence intervals by factors (separately and together); graphical examination of the normal distribution; test of homogeneity of variances with Bartlett Chi-Square test; two-factorial ANOVA; and the Duncan test as a post hoc test. The soil parameters of the pots of different treatments were compared in both the first and second years of the experiments and between the two consecutive years. Plant growth parameters were compared between treatments in each year separately.

3 RESULTS

3.1 Relationships between treatments and soil parameters

Table 1 shows the soil analysis data for both consecutive years. Based on substrate pH(H_2O)-values, the red mud treatment significantly altered the chemical state of the soil as expected. In the control samples, the sewage sludge developed a weakly acidic pH in the first year, while the values increased to slightly alkaline with the addition of red mud. The red mud exhibited no change in the second year, and the initial acidifying effect of the sewage sludge disappeared by the second year in the control plots, as shown by the increase in the mean pH values.

Water-soluble salt concentrations were relatively high in the first year; on a scale comparable to that of low-salinity, saline soils. This is mainly due to the well-known high salt content of municipal sewage sludge caused by detergents, but the red mud also contained soluble Na salts. By the second year, salt concentrations decreased significantly (<0.1%) (*Figure 3*). The artificial provision of climate-appropriate rainfall amounts (supplemented up to the amount of the mean average precipitation of the growing season, 390 mm, added on a bi-weekly basis, 151 mm in the first year, 168 mm in the second) allowed the salinity of the soil mixtures to normalize within a year, with soil mixtures transformed from a saline status into soils with non-saline soil properties.

Table 1. Means and homogeneous subsets of soil parameters of the two consecutive years of the pot experiment.

Variable	1st year Mean/hom.subset*			2nd year Mean/hom.subset*		
	Control	RM15	RM30	Control	RM15	RM30
pH(H_2O)	7.6^{a}	7.5^{b}	7.6^{b}	7.4^{c}	7.6^{b}	7.6^{b}
total soluble salt (%)	0.18^{a}	0.16^{a}	0.23^{b}	0.07^{c}	0.04^{d}	0.09^{c}
$CaCO_3$ (%)	7.8^{a}	5.0^{b}	3.8^{c}	6.2^{d}	4.2^{bc}	2.7^{c}
H (%)	3.8	4.4	4.0	3.6	4.4	3.6
AL-P_2O_5 (mg/kg)	2863	1883	1394	1591	1464	1152
AL-K_2O (mg/kg)	543	573	449	216	252	257
AL-Na (mg/kg)	397^{a}	3974^{b}	5133^{c}	406^{a}	2747^{d}	5138^{c}
KCl-(NO_2+NO_3)-N (mg/kg)	317^{a}	302^{b}	320^{a}	64^{c}	76^{c}	134^{d}
KCl-SO_4^{2-}-S (mg/kg)	205^{a}	138^{b}	208^{a}	153^{c}	75^{d}	149^{c}
KCl-Mg (mg/kg)	539^{a}	335^{b}	370^{c}	466^{d}	374^{c}	339^{b}
EDTA-Cu (mg/kg)	18^{a}	21^{b}	20^{c}	18^{a}	23^{d}	20^{c}
EDTA-Mn (mg/kg)	37^{a}	38^{a}	53^{b}	30^{c}	34^{a}	42^{d}
EDTA-Zn (mg/kg)	23^{a}	22^{b}	21^{c}	23^{d}	22^{b}	21^{c}

**small letters (a, b, c) indicate homogeneous subsets according to Duncan-test procedure; colour codes: black letters indicate common values for soils in Hungary; orange – unfavourable values for plants; green – good conditions*

The $CaCO_3$ content was high in the control mixture, typical for the loess bedrock (Stefanovits et al. 1999), and only moderate in the red mud mixtures. Red mud contains no $CaCO_3$ due to the intensive leaching during bauxite formation. Hence, $CaCO_3$-proportion naturally decreases with the mud addition. Data from the two study years revealed that lime leaching was relatively rapid.

In the case of humus-related organic carbon contents expressed in H% on a theoretical basis (H%=C_{org}%*1.72 (Stefanovits 1999)), no significant difference could be described based on the statistical analysis. Although the samples proved to be normally distributed, the homogeneity of the standard deviations was not given. Therefore, the values can be considered of the same order of magnitude, and no significant differences were found.

The amount of ammonium-lactate-soluble P_2O_5 (AL-P_2O_5) was significantly higher in the control samples than in those treated with red mud. Such differences were not detected between the red mud treatments. Concerning plant nutrition, phosphorus uptake in all three media refers to excellently supplied soils (Buzás 1999), regardless of significant differences between the samples. By the second year of the study, the AL-P_2O_5 content was significantly reduced for both treatments and the control.

The AL-K_2O values scattered highly, so no normal distributions were found, and the homogeneity of variances was not ensured, indicating that the results cannot be proven statistically. The magnitude of potassium available to plants was very high in the first year for all three substrate types. Values decreased in the second year.

Upon examining the amount of AL-soluble Na, the Na content of the control samples was significantly lower than that of the samples treated with red mud. The same results were shown for both consecutive years of the study, and no clear changes with time were detected.

The KCl-soluble nitrite + nitrate contents displayed no significant difference between the treatments in the first year, but values were on the level of good N-supply for plants from soil

(Buzás 1999). We found much lower values in the second year. Unfortunately, sample homogeneity was inadequate, which prevented the verification of statistical differences.

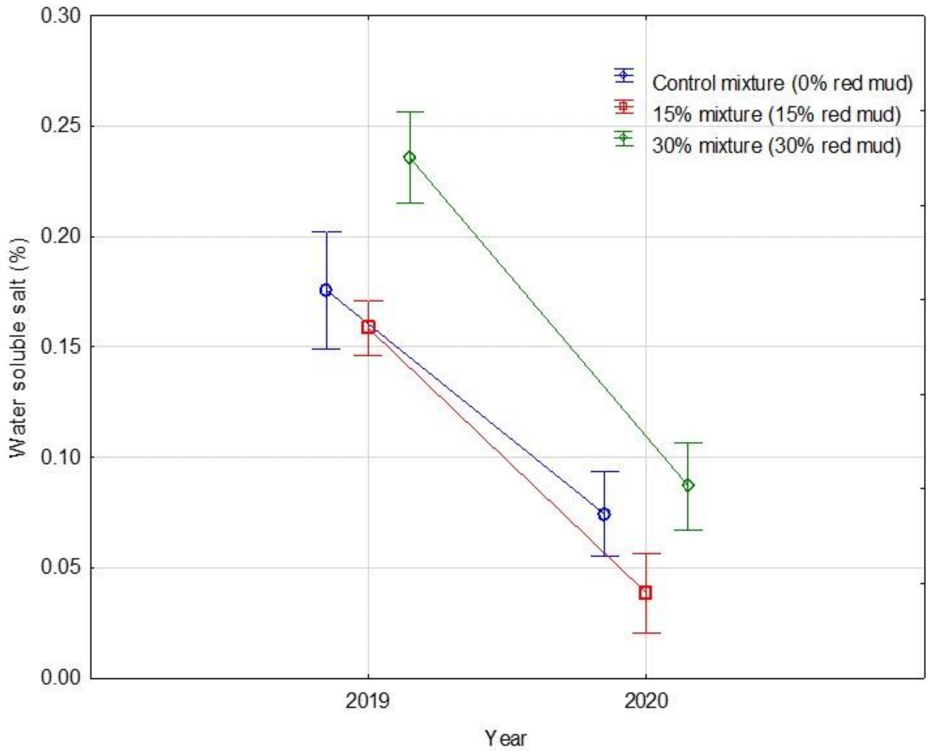

Figure 3. Means and 95% confidence intervals of water-soluble salt contents in the two consecutive years of the open-air pot experiments with red mud treatments.

The KCl-soluble sulphate content for RM15 was considerably lower in both years compared to the control and RM30. In addition, significantly lower concentrations were measured in the second year for all three substrates. The high sulphate content provided a good supply to the plants in both the first and second years.

Significantly higher values for KCl-soluble Mg contents were measured in the control than in the red mud mixtures. No clear trend emerged over time. While the control and RM30 showed significantly lower magnesium values in the second year, the RM15 showed the opposite, a significant increase.

Based on the present statistics, EDTA-extractable copper content exhibited no clear difference between the treatments or the years. Copper content was only slightly increased in the samples treated with red mud, but the RM15 values were higher than the RM30 values.

The addition of red mud considerably increased the EDTA-extractable Mn contents in the soil mixtures. Although Mn levels decreased over time for all three substrates, they remained high.

The addition of red mud significantly decreased EDTA-extractable Zn contents in the soil mixtures. However, a slight increase in concentrations over time was not statistically significant. These values are favourable for the nutrient supply; there will be no limiting factor for plant growth.

The bulk density determined at the end of both growing seasons for the RM30 was 0.89 g/cm^3, 0.90 g/cm^3 for RM15 and 0.94 g/cm^3 for the control. We detected no significant differences between these values nor in the relationship between the bulk density and the soil samples of each plant species.

3.2 Relationships between plant growth parameters and treatments

Table 2 presents the height, the stem diameter, the aboveground stem+shoot-biomass and the belowground root-biomass measured in the second year of the experiment for each plant species per treatment. Pekler published first-year data in 2020.

Table 2. Means and homogeneous subsets of plant growth parameters in the second year of the pot experiment.

Variable	ARUN.	ARTIC.	SIDA	ROBIN.	POPU.	QUER.	ACER	ULMUS
Height (cm)								
Control	109[a]	144[a]	124[a]	95[a]	99[a]	23[a]	46[a]	115[a]
RM15	115[a]	148[a]	137[a]	150[b]	137[b]	23[a]	61[b]	156[b]
RM30	97[a]	145[a]	134[a]	148[b]	121[a]	19[a]	21[c]	146[b]
Above ground biomass (g/pot)								
Control	210[a]	785[a]	383[a]	142[a]	146[a]	11.9[a]	20.5[a]	317[a]
RM15	104[b]	844[a]	474[a]	257[b]	299[b]	12.8[a]	38.0[b]	425[b]
RM30	61[c]	711[a]	435[a]	315[c]	145[a]	6.3[a]	13.0[c]	466[b]
Belowground biomass (g/pot)								
Control	278[a]	853[a]	516[a]	83[a]	95[a]	16.4[a]	29.4[a]	151[a]
RM15	231[b]	915[a]	396[a]	163[b]	272[b]	27.9[a]	54.6[b]	255[b]
RM30	141[c]	907[a]	317[a]	157[b]	209[b]	15.0[a]	24.5[a]	189[a]
Stem diameter (mm)								
Control	-	-	-	11.3[a]	13.1[a]	5.8[a]	6.5[a]	15.5[a]
RM15	-	-	-	15.2[b]	17.6[b]	5.8[a]	8.1[b]	17.9[a]
RM30	-	-	-	14.8[b]	12.7[a]	4.9[a]	4.6[c]	17.8[a]

small letters (a, b, c) indicate homogeneous subsets according to the Duncan-test procedure.

Arundo showed no different plant heights from red mud treatments. However, the aboveground and the belowground biomass significantly decreased as the red mud addition increased.

Jerusalem artichoke exhibited no notable difference in terms of either aboveground biomass, underground biomass or height between treatments.

Based on the statistical analyses, the same can be said for Sida, even if the belowground biomass seemed to decrease with the addition of red mud. However, the aboveground biomasses were approx. 15–25% higher than the control.

Due to its intensive growth, the roots of the black locusts largely filled the entire volume of the culture pots by the end of the growing season, which limits the comparison of the data magnitude. The height growth of black locust was best with RM15. A significant difference was found compared to the control but not between the mud treatments. Aboveground biomass was highest for RM30, but this positive effect was not significantly proportional to the amount of red mud. The same positive influence of red mud was found for root mass, and again no significant differences were found between different proportions of red mud. Differences in stem diameter show a positive effect only for RM15 treatment.

The height increment of white poplar was significantly higher for the RM15 compared to the other two treatments, where no such difference could be reported. The same statistically significant pattern was detected for the aboveground biomass and stem diameter. Belowground biomass was again higher for both mud treatments, but in this respect, RM30 was not significantly behind RM15.

Plant parameters of pedunculate oak did not meet the assumptions of ANOVA since both the normality and the homogeneity of variances were violated. This means that the differences between treatments cannot be proven statistically. Still, while no RM15 effects were visible, a slight decrease in plant height, aboveground biomass and stem diameter was detected for RM30.

Field maple grows better with the RM15 as in the control mixture, but the higher dose already had a limiting negative effect. This was observable for height, aboveground biomass and stem diameter. Only in belowground biomass did RM30 not differ from the control.

The height and aboveground biomass of Siberian elm plants were considerably higher in the red mud-treated soil mixtures than in the control. The root biomass (*Figure 4*) showed quite the same effect, but with RM30, this difference was not significant. The roots showed such intensive growth that they nearly filled the entire volume of the culture pots by the end of the growing season, which again limited the magnitude assessment of the data. Although stem diameter was slightly higher for both mud treatments, no significant difference was detected.

Figure 4. One-year-old Siberian elm roots (Ulmus pumila L.*) washed for weight; measurement at the end of the second year of the experiment.*

4 DISCUSSION

As expected, the red mud treatments caused significant changes in the chemical status of the soil mixtures, the extent of which was demonstrably related to the intensity of the treatments for several parameters.

Soil pH(H_2O) values presumably indicated that the organic acids previously present in the soil solution were leached and/or bound on the mineral surfaces of the fine particles of red mud. Similarly, the initial high amounts of salts not bound by organic compounds were largely leached during the experiment. Compared to the experiment of Lockwood et al. (2015) – who investigated the polluting effects of red mud that reached the ground in connection with the red mud spill in Ajka in 2010 – our mixtures exhibited a much smaller pH-value increase. The pH values of the original soil in Lockwood et al. were 7–8 in the 33%. The red mud mixture increased these to 9.5–11.5, and in the 9% red mud mixture, to 8.5–10.0 in different types of soil. Our study observed a pH increase of only 0.2–0.9, likely due to the compensatory effect of the organic acids found in large quantities in sewage sludge, which neutralized alkalinity.

At the same time, we reduced the drastic pH-increasing effect of the red mud in soil much more effectively than what Lockwood et al. were able to achieve in damage prevention at the time with the Dudarit (lignite-based additive) treatment used during the Ajka disaster: Filep et al. (2015) described only a minor change from 9.49 to 9.33 with their highest mud addition treatment. Szabó (2011) reported toxic effects starting at pH-level 10.5 upwards in a soil column experiment with different red mud contamination levels. This supports our conclusion that the pH values of our substrates do not present any risk for soil biology.

High soluble salt contents had a magnitude comparable to saline soils (salinity class II on a III-step Hungarian scale (de Sigmond 1927)) in the first year. This is probably unfavourable for plants lacking proper mechanisms to deal with this. It can cause problems for the water and nutrient management of plants and, ultimately, for land use. However, salt concentrations decreased in the second year under the 0.1% limit, under which soils are not classified as saline. With this, a significant expansion of the range of applicable plant species is expected (Tóth 2010).

While in the first year of the treatment, salt contents of the substrates were high compared to forest soils of Hungary, the treatments slightly decreased the $CaCO_3$ content. $CaCO_3$ ‘dilution’ caused by mixing in the mud low in carbonate due to the former strong leaching of bauxite was a positive effect – taking into account the local climate – decreasing the negative impact of $CaCO_3$ on the amount of water available to plants (Füleky 2011). Therefore, this change can be assessed as beneficial for the vegetation. The relatively fast leaching of calcium carbonate during the experiment can probably be deduced from the acidity of rainwater and sewage sludge.

The amount of organic matter corresponds to that of natural soils with a good supply of nutrients. The presence of a Mollic horizon is one of the most important diagnostic criteria of the naturally occurring Kastanozems soil type in the surroundings of our experimental area (IUSS Working Group WRB, 2022). Their average humus contents in the area are between 1.3–2.5% (unpublished soil survey data of the authors Kovács and Heil), whose values are much lower than those of our substrates. If the mineralization processes can take place – based on our previous studies on the artificial soil mixture (Lachmann 2018) – it is expected that the organic matter will stabilize quickly compared to the natural soil formation processes, with the formation of organic-mineral complexes. At the end of the two-year experiment, stable soil and pore structure could be seen, enabling the presence of earthworms (*Figure 5*).

Anton et al. (2012) modelled the potential effects of the Hungarian red mud disaster in Ajka in 2010. Based on their results, we assume this process is accelerated due to the fine grain distribution of red mud (on average about 40% silt, 50% clay content) and the large specific mineral surface area resulting from the latter.

All three substrates had high amounts of ammonium-lactate soluble phosphorus (P) available for plants in the soil solution (Füleky 1999). The pH of the medium decreased with the addition of red mud, which leads us to believe that the P in the organic-mineral bonds formed in the alkaline medium was converted to an insoluble form, so its uptake decreased with increasing pH. Previous studies demonstrated that red mud can bind high amounts of dissolved phosphate and is, therefore, also used as an adsorbent (Huang et al. 2008). Similarly, the presence of secondary $CaCO_3$ in the substrates originating from the loess parent material contributes significantly positively to reducing leaching losses of P through the secondary precipitation of Ca–P minerals and/or a strong sorption reaction of P with $CaCO_3$, as shown by Carreira et al. (2006).

Third, the addition of red mud simultaneously reduced the proportion of high-P sewage sludge within the mixtures. When the amount of P leached from each culture pot during the study is converted to 1 hectare of production area, 134 kg P/ha is obtained for the control, 44 kg P/ha for RM15 and 26 kg P/ha for RM30. As a comparison, ca. 2.92 kg P/ha active ingredient must be added to reach 1 t/ha yield of agricultural crops (Füleky 1999).

Figure 5. Initial soil formation resulting in soil structure can be detected with the naked eye, during the breaking of the pots in the second year of the experiment.

No effects on AL-K_2O could be linked statistically to the red mud treatments. We assume that the original bauxite leaching removed most of the potassium from the mineral particles of red mud; however, a sufficient amount remained from the loess, so no resulting nutrient deficiency symptoms are expected (Buzás 1999). Ujaczky et al. (2014; 2015) found similar values of AL-K_2O in artificial soil-red mud mixtures ten months after their field trial started. They measured average concentrations of 217 mg/kg for a 20 vol% red-mud/soil mixture and 256 mg/kg for a 50% mixture, representing an average to good supply for plants.

The sewage sludge was the main source of sodium in the soil mixtures, originating typically from the salt content of foods and detergents. Adding red mud caused a strong mobilisation of this ingredient, resulting in very high concentrations available to plants. This may be related to the poorer growth of some plant species in the red mud treatments. The Na amounts were still quite high in the red mud treatments in the second year; thus, the Na tolerance of plants is probably required. Feigl et al. (2013) set a limit of 600 mg/kg AL-Na as an indicator of the red-mud contaminated soils after the Ajka spill: the initial toxic effects on the test organisms *Vibrio fisheri* (bacteria), *Lemna minor* (aquatic plant), *Sinapis alba* (plant) and *Heterocypris incogurens* (ostracod) only occurred with 20-30% red mud contamination.

Due to the alkalinity of the soil solution of the soil substrate treated with red mud, variable charge surfaces are mostly terminated by nonbridging hydroxyls carrying a partial negative charge, which impedes nitrate-nitrite bonding. These readily soluble nutrient forms experienced rapid leaching over time. If the amount of nitrogen leached from each culture vessel is converted to 1 hectare of production area, 109 kg N/ha is obtained for the control, 98 kg N/ha for RM15 and 80 kg N/ha for RM30. This is the amount of the additional nitrate supply from precipitation for this region. However, the source of these N-forms was not the red mud that is the focus of our present study, as the field experimental results of Feigl et al. (2013) prove. They measured concentrations of only 1.2–1.7 mg NO_3-N/kg in their soil samples mixed with red mud in the area of the Ajka reservoirs.

The amount of KCl-soluble sulphates easily absorbable by plants was significantly reduced with RM15, but again, it did not differ from the control with a higher dose of red mud. Under aerobic conditions of the upper soil layers – with similarly low bulk density values as our soil mixture shows – sulphur is mainly present in organic bonds. As we have seen, H% values were highest for RM15, while they were approximately the same for the other two substrates. This may explain the similar evolution of sulphate concentrations. Although Feigl et al. (2013) determined total sulphur contents in their experiment on red-mud-contaminated soils, they did not find increased concentrations due to red mud compared with the control. Overall, sulphate concentrations of all three substrates were so high that the plants had adequate sulphur supply (Buzás 1999).

The concentration of KCl-Mg in the red mud is much lower than in the base soil mixture; it is obvious that the magnesium concentration decreases when it is added. However, the extent of this reduction is insufficient to have the expected negative effect on plant growth. For arable soils, Mg contents above 200 mg/kg can be considered as well supplied, which is true for all soil mixtures of the clayey and loamy types (Buzás 1999).

Above 3.2 mg/kg EDTA-extractable copper concentrations, arable land is considered to be well supplied. This value was significantly exceeded in our mixtures. According to KvVM-EüM-FVM Joint Decree No. 6/2009. (IV. 14.) on the limits needed for the protection of water and soil against pollution and the measurement of pollution, this quantity is still far below the contamination limit value, so no direct harmful effect on plant growth is expected. Anton et al. (2012) also found red mud entering the soil did not cause toxic heavy metal concentrations.

The manganese content available to plants from the soil mixtures increased with the increasing amount of red mud in the pots with RM15 and RM30. This element behaves like iron in soils, presumably appearing in the red mud in an absorbable form, which explains such an effect. Arable soils can be considered well supplied – with a clayey soil texture in the neutral pH range – from an EDTA-soluble Mn concentration above 30 mg/kg (Buzás 1999). Overall, this shows that all of our mixtures ensure a good supply of Mn.

The physical properties of the soil are determined by the properties of the raw materials of the mixture. These properties changes are difficult to track during the short duration of the experiment, and former studies indicated no detectable changes in this manner (Anton et al. 2012). We examined only the bulk density because it is closely related to mixing quality and refers to the framework for water and air management of the resulting mixtures. Bulk densities can be considered low for all substrates, and are usually found in cultivated upper layers of arable soils or upper layers with high humus contents of forest soils. This shows that in one year, the root system does not affect the soil structure to such an extent that it can have a detectable effect on bulk density neither for herbaceous nor for woody vegetation.

The plant species included in the study responded differently to the red mud treatments. Among the herbaceous plants, giant reed, known for its intensive biomass production and grown for energetic purposes, exhibited good growth in our previous experiment (unpublished) in our basic mixture used here as control. Nevertheless, with the addition of red mud we observed growth inhibition and this negative effect even increased with higher mud concentrations. This contradicts Nsanganwimana et al. (2014), who recommended *Arundo donax* plantations for phytomanaging constructed wetlands, marginal and contaminated sites.
The red mud treatments had no statistical effect on Virginia mallow and Jerusalem artichoke, the other two herbaceous species. Notwithstanding, our results could address some of the research gaps Nahm and Morhart (2018) mention for *Sida*, which are needed for a wider use of

this plant in Central Europe. Similar to recent literature reviews, our results support Abdalla et al. (2014), who suggested that the artichoke should be used more widely in recultivation areas, and Rossini et al. (2019), who recommended its use as a sustainable energy crop.

In our experiment, we used tree species widespread in Hungarian forestry practice and known for their tolerance to high salt concentrations and drought. To compare tree dimensions with the forestry practice, we used quality requirements on forest reproductive material described for the purpose of defining "common commercial quality" in the 110/2003. (X.21.) decree of the Ministry of Agriculture. With tree species where the legal provision did not prescribe requirements for certain parameters, we compared the growth of our plants to the size of the propagating material traded in the Hungarian forestry trade.

The height growth of the black locust reached that of best-quality class seedlings in Hungarian forestry practice. Root development did at least reach the minimum requirements of 25 cm depth after one year, but the pot size limited growth. Both aboveground and underground biomass showed that black locust biomass was significantly higher in the mixture treated with red mud than in the control, even if this tree species is known not to tolerate higher salt conditions seen in the mixtures with mud. This clearly shows the beneficial effect of red mud on the growth of *Robinia* seedlings.

For white poplar, dimensions exceeded those of normal seedlings used in forestry practice. The most vital growth of these plants was found for RM15. With the addition of higher amounts, plant growth was the same as in the control. White Poplar in forests can tolerate salt contents of 0.1–0.2% (Járó 1960), but probably due to the higher Na-concentrations, tolerance limits were reached in this study.

Pedunculate oak demonstrated good growth in all three substrates; even if a slight but statistically unverified decrease in plant dimension was found with RM30. However, our seedlings still reached all minimum requirements for use in forestry practice (height min. 18 cm, diameter min. 4 mm, root length min. 20 cm).

The treatments caused field maple to behave like black locust. RM15 was the best medium in the critical first year of growth for this species.

Finally, the Siberian elm achieved the strongest growth and highest biomass production among tree species. The species was unquestionably able to make the best use of the conditions our artificial soil mixtures provided.

When comparing the ability of colonization of surfaces covered by pure red mud (Terpó – Bálint, 1985) with that on our substrates, we could present a good alternative for the ecological utilization of red mud.

5 CONCLUSIONS

Our study investigated whether the use of a well-proven sewage sludge combined mining reclamation method can be combined with the high-volume, low-cost utilization of additional waste material – red mud. In our artificial soil mixtures, we examined the growth of herbaceous and woody plant species widespread in Hungarian agricultural and forestry practices. Of the herbaceous species included in the experiment, the addition of red mud inhibited only giant reed growth. Jerusalem artichoke and Virginia mallow developed similarly well to the control medium. Woody plants taken from forestry practices all exhibited good growth. Red mud treatment was particularly beneficial for black locust and Siberian elm. According to these first studies, we consider it worthwhile to scale up this cheap, economically and ecologically favourable combined waste recovery and mine reclamation technology, to test the innovation in an operational business environment and to grow its use to full-scale operation.

Acknowledgements: The financial support of Széchenyi 2020 under GINOP-2.2.1-15-2017-00106 is gratefully acknowledged.

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