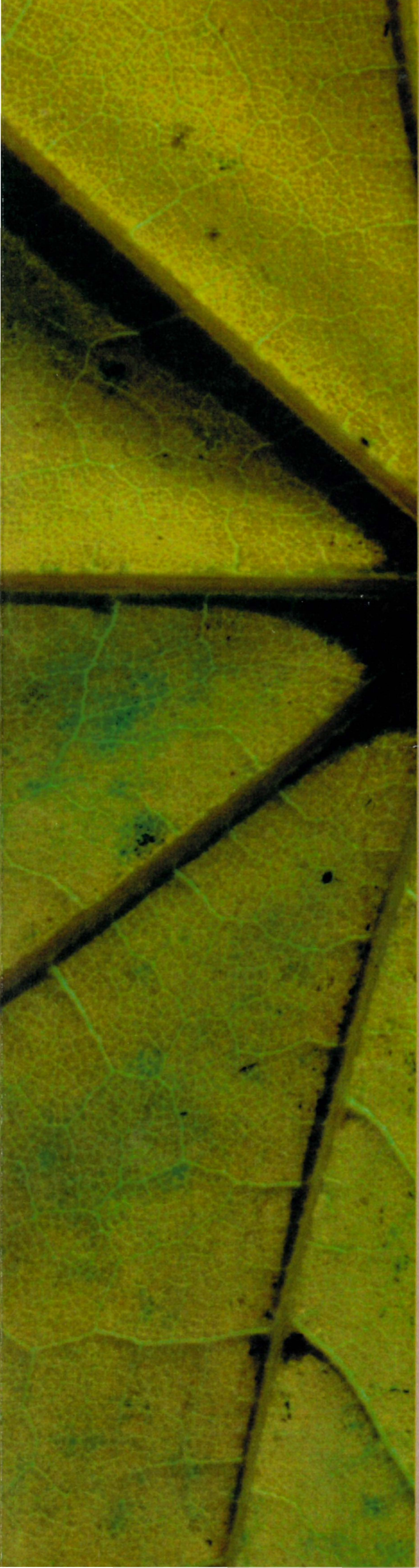

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Manuscripts and editorial correspondence should be addressed to
TAMÁS HOFMANN, ASLH EDITORIAL OFFICE
UNIVERSITY OF SOPRON, PF. 132, H-9401 SOPRON, HUNGARY

Phone: +36 99 518 311
E-mail: aslh@uni-sopron.hu
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Tartalomjegyzék

Social Network Analysis in Wood Industry Projects

Adrienn NOVOTNI* – Zoltán PÁSZTORY – Zsolt TÓTH

Faculty of Wood Engineering and Creative Industries, University of Sopron, Hungary

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.

* Corresponding author:novotni.adrienn@uni-sopron.hu; H-9400 SOPRON, Bajcsy-Zs. u. 4., Hungary

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:

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

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

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

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:

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

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:

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

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:

$$L = \frac{1}{2}\sum_{i=1}^{N} k_i \tag{5}$$

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:

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

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:

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

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:

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

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:

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

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:

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

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.

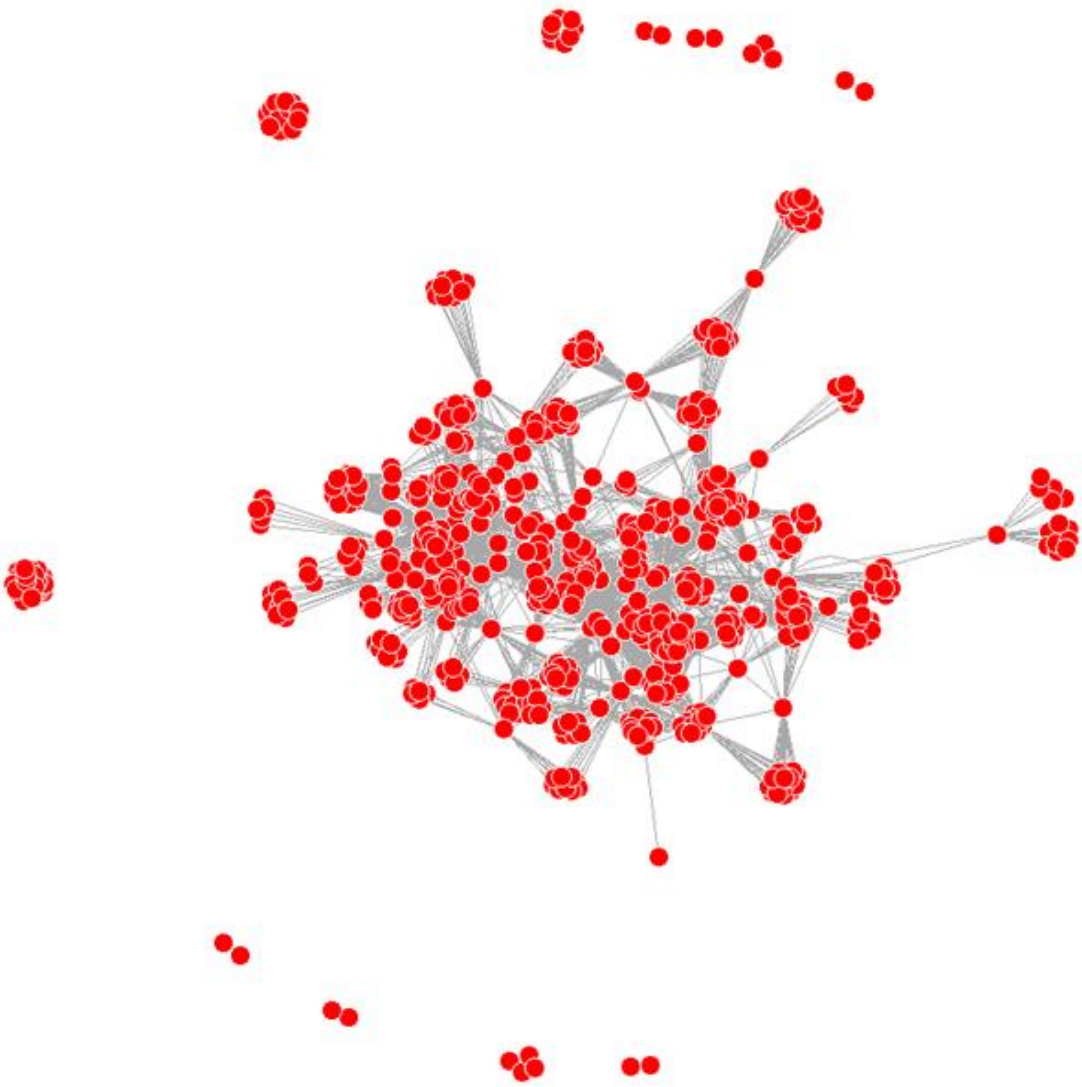

Figure 1. Network of project participants

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.

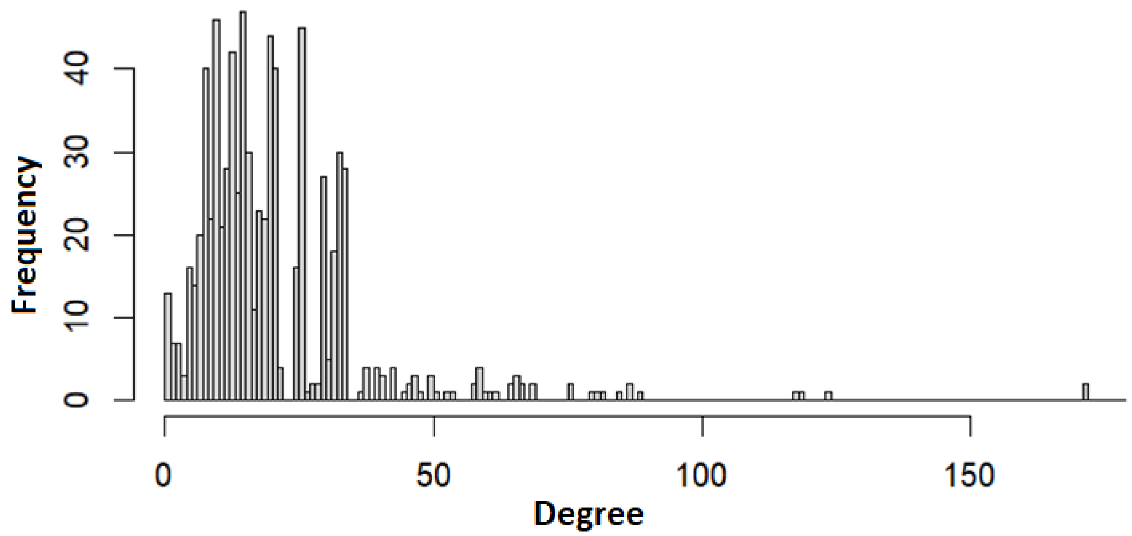

Figure 2. Frequencies of degrees

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.

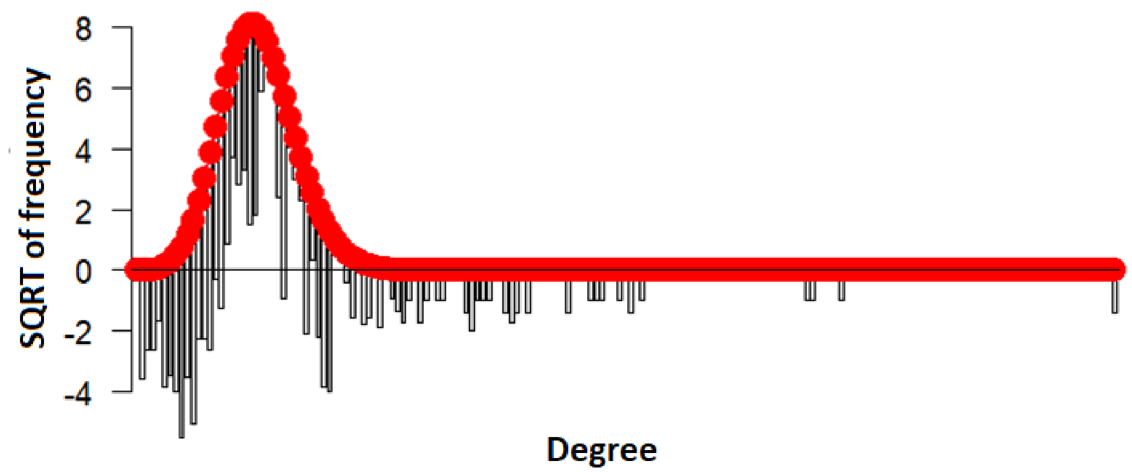

Figure 3. Rootogram of degrees

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*).

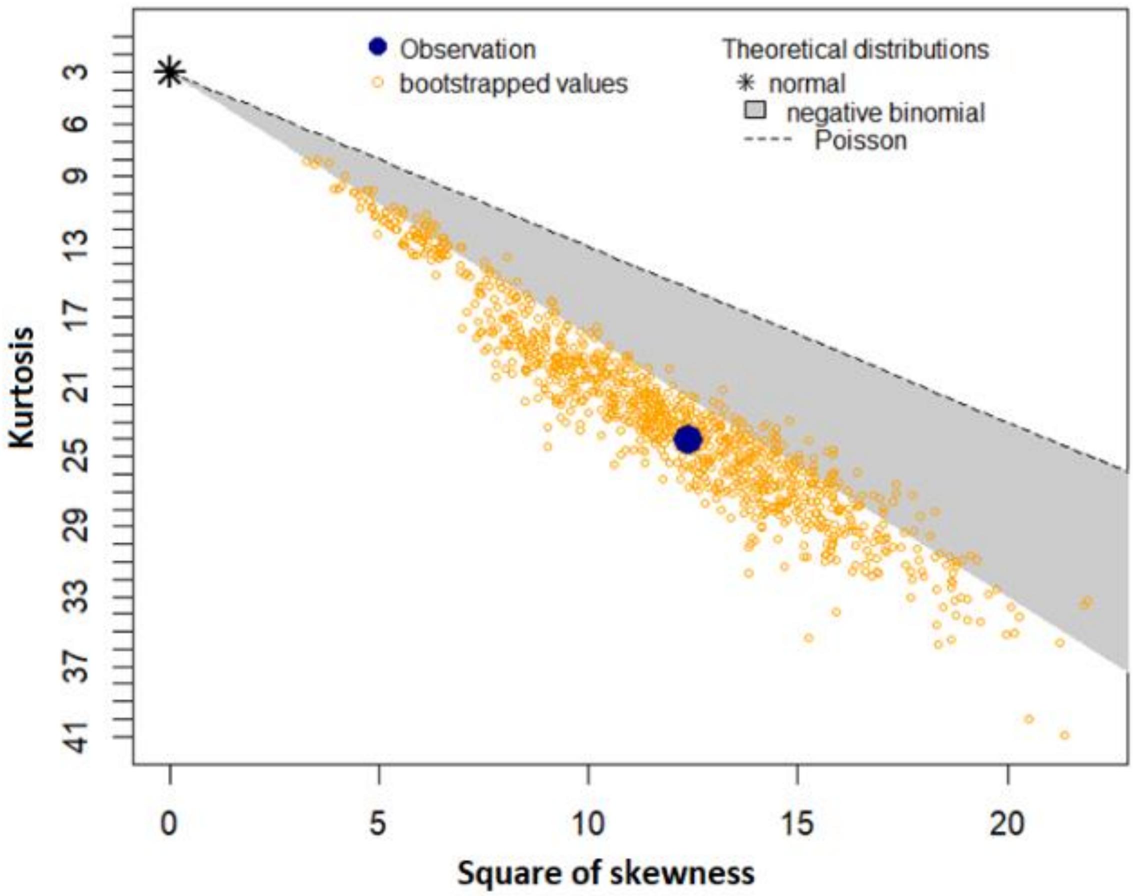

Figure 4. Cullen and Frey graph (discrete variable)

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.

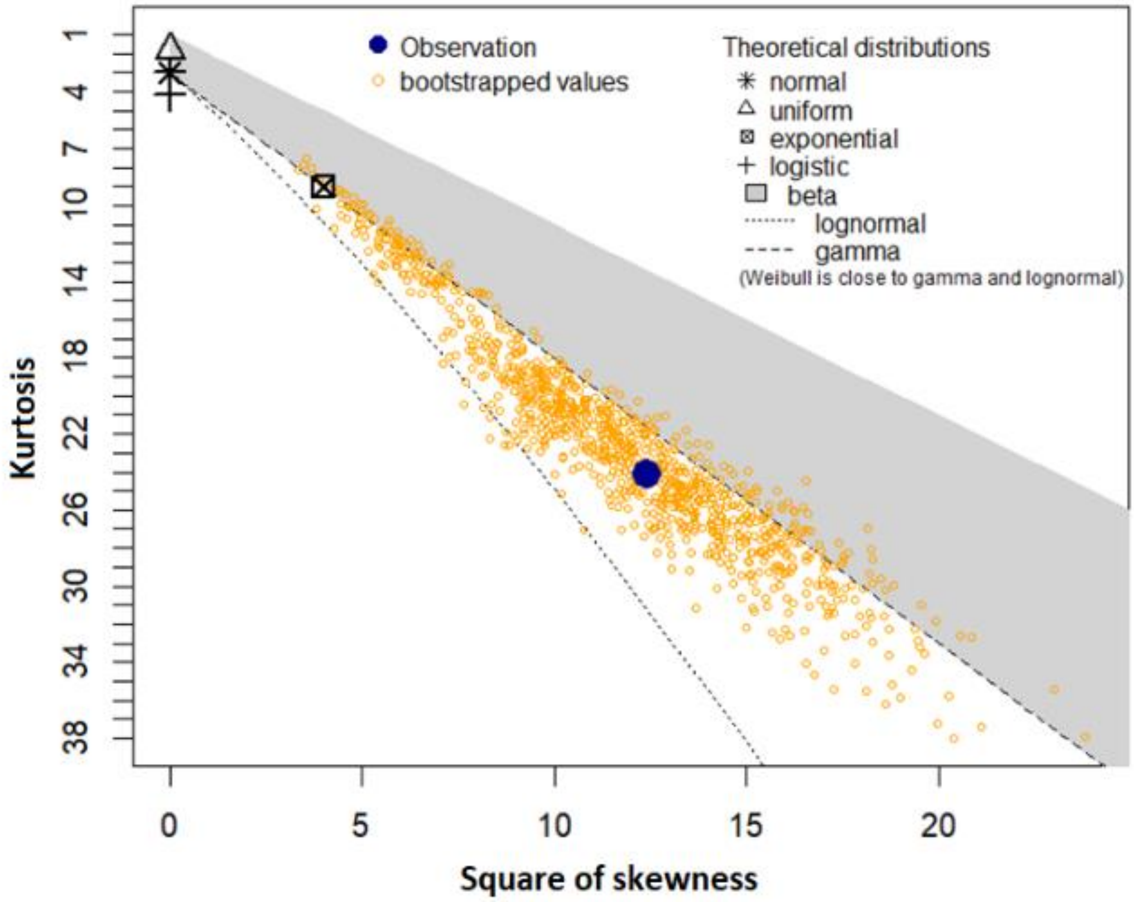

Figure 5. Cullen and Frey graph (continuous variable)

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.

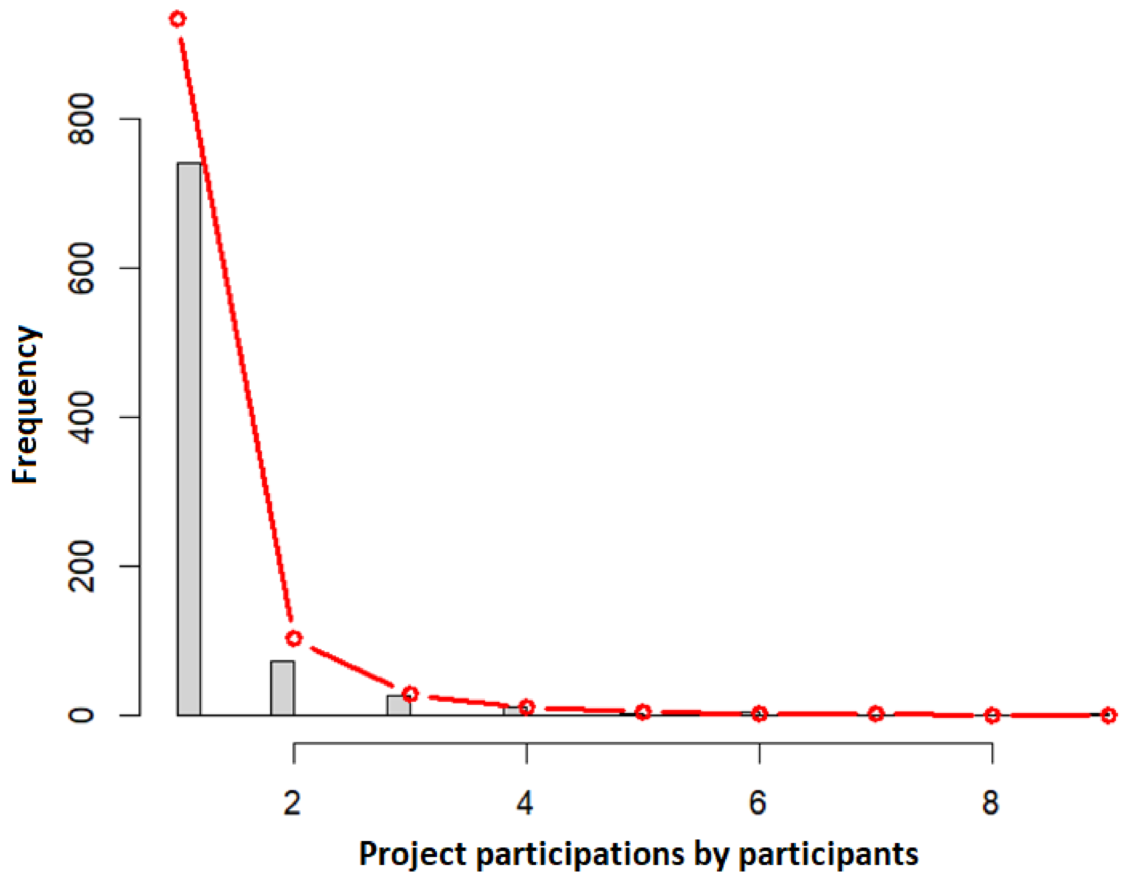

Figure 6. Frequency of participations

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.

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

Tamás MOLNÁR[a,b*] – Géza KIRÁLY[b]

[a] University of Sopron, Forest Research Institute, Department of Ecology and Silviculture, Budapest, Hungary
[b] Institute of Geomatics and Civil Engineering, Department of Surveying and Remote Sensing, University of Sopron, Sopron, Hungary

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

[*] Corresponding author:molnar.tamas@uni-sopron.hu; H-1027 BUDAPEST, Frankel Leó u. 1., Hungary

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*).

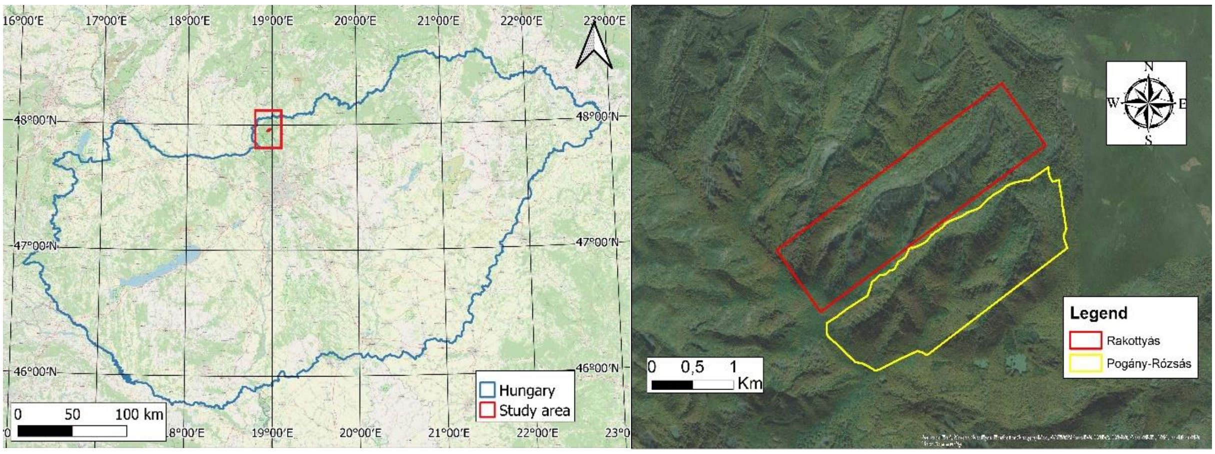

Figure 1 a, b. Börzsöny Mountains in Northern Hungary (a), which contains the two study sites, the Rakottyás (north) and the Pogány-Rózsás (south) valleys on Google Maps aerial image in 2021 (b)

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.

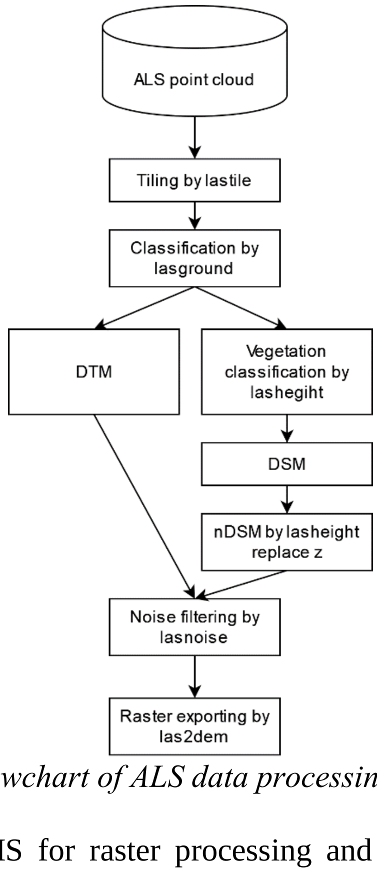

Figure 2. Flowchart of ALS data processing in Lastools.

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*).

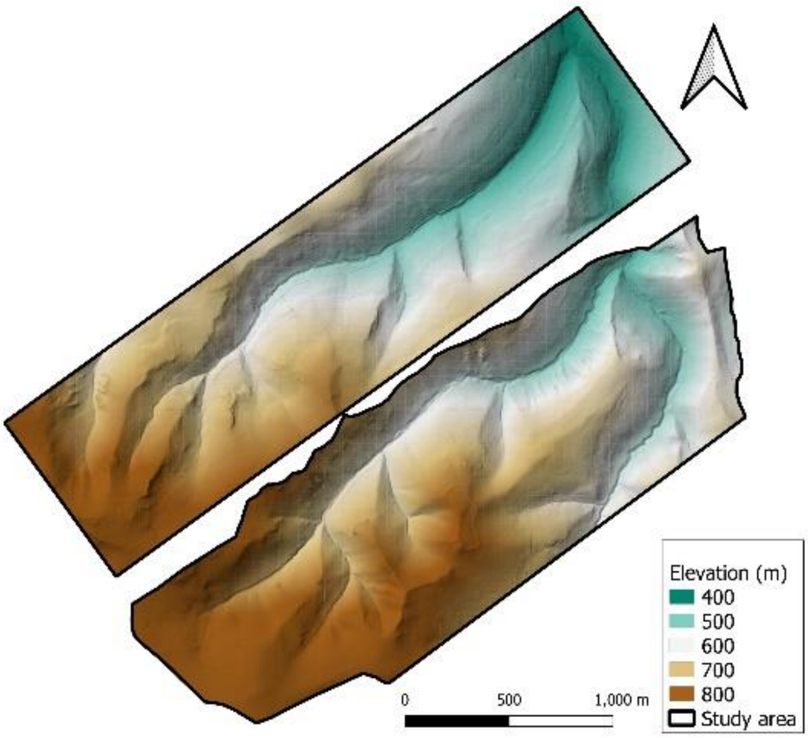

Figure 3. Elevation of Rakottyás and Pogány-Rózsás valleys based on DTM. Pogány-Rózsás is situated at higher mean elevation (696 m) then Rakottyás (632 m)

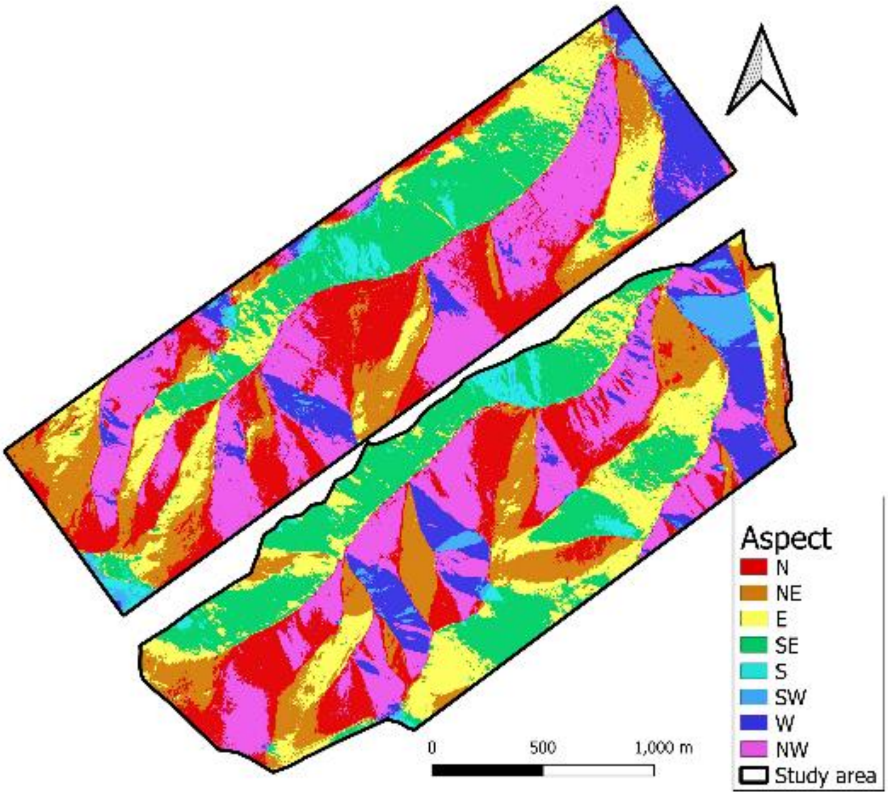

Figure 4. Aspect of Rakottyás and Pogány-Rózsás valleys based on DTM. The most typical slopes are the northerly in Rakottyás and east-facing ones in Pogány-Rózsás

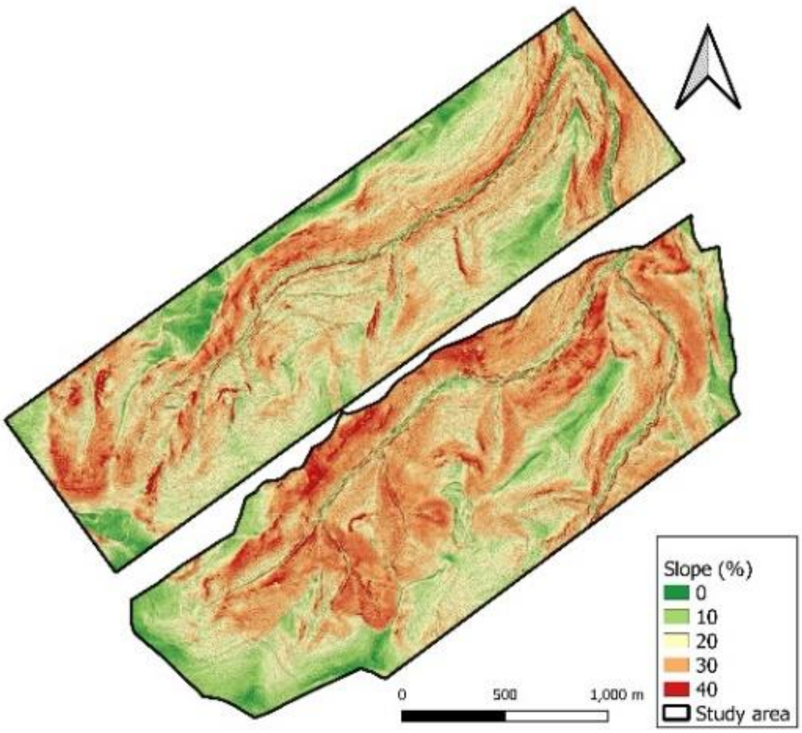

Figure 5. Slope of Rakottyás and Pogány-Rózsás valleys based on DTM. Pogány-Rózsás is slightly steeper (46% in mean) then Rakottyás (42%), but less damaged

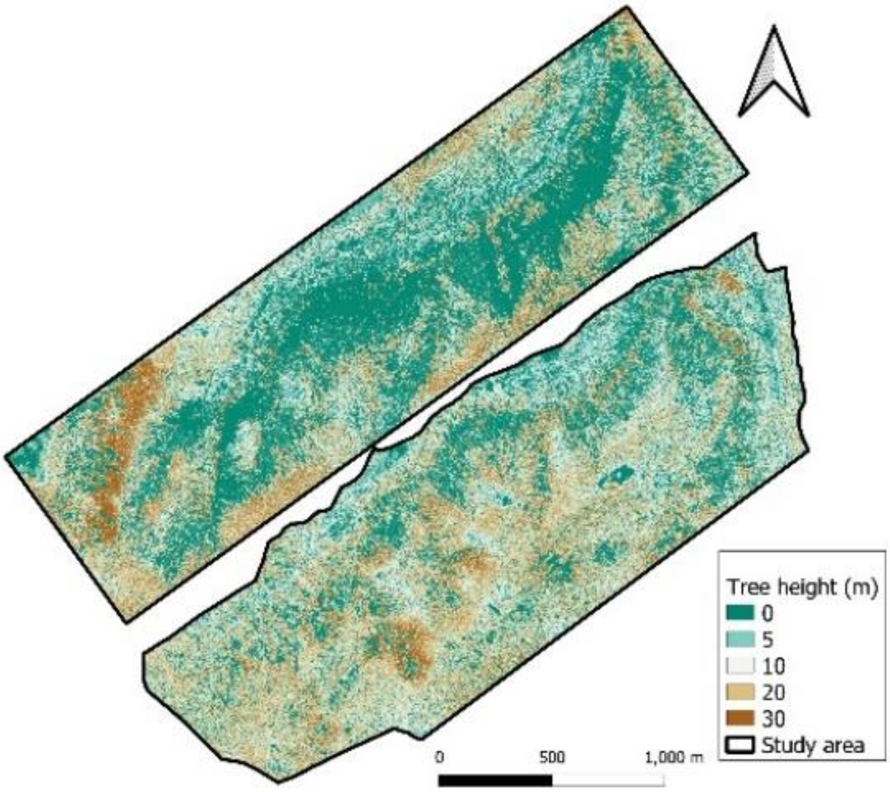

Figure 6. Vegetation height of Rakottyás and Pogány-Rózsás valleys based on nDSM. Pogány-Rózsás had more heterogenic forest heights, i.e., more small-scale differences, while the forest height in the managed Rakottyás was more homogeneous; however, this is due to the larger flat area caused by the damage

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

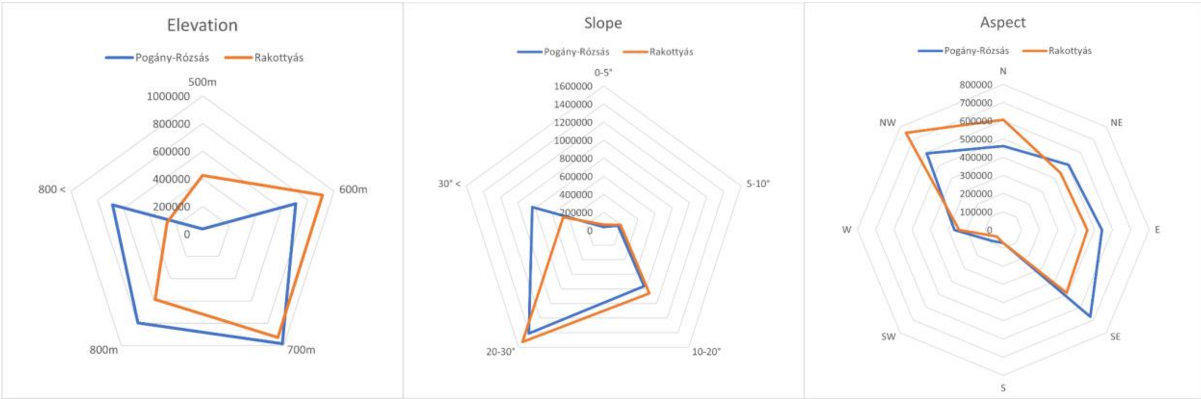

Figure 7. Elevation (a), slope (b), and aspect (c) conditions of Rakottyás and Pogány-Rózsás valleys based on DTM. The most frequently damaged slopes are the NW-facing in Rakottyás and the SE ones in Pogány-Rózsás. Steep slopes between 20–30° are the most frequent, and 700 m is the most typical height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

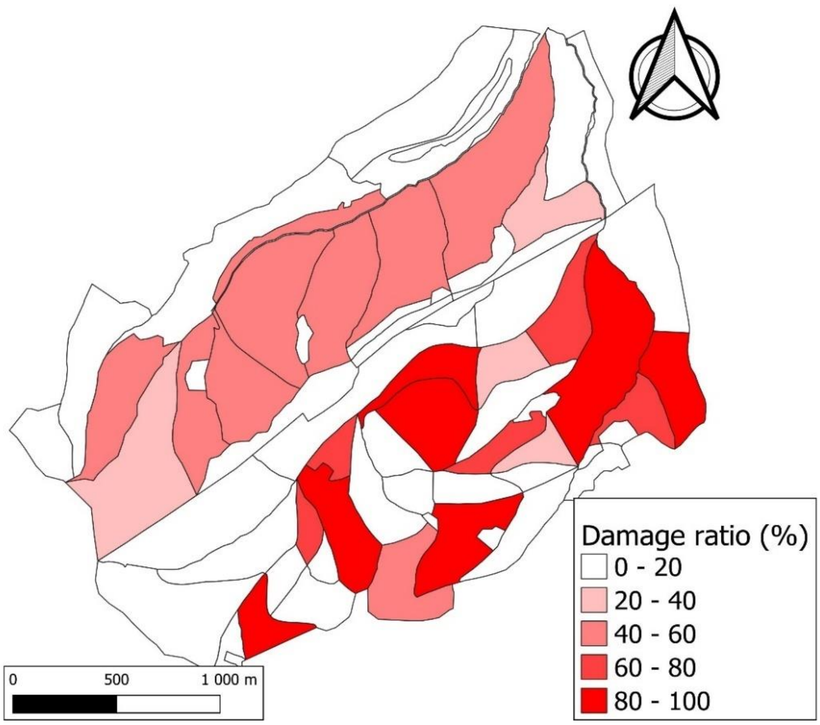

Figure 8. Ground-based damage ratio in Rakottyás and Pogány-Rózsás valleys. The difference between the damage severity and the size and number of compartments is visible in the two valleys.

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 (%)		

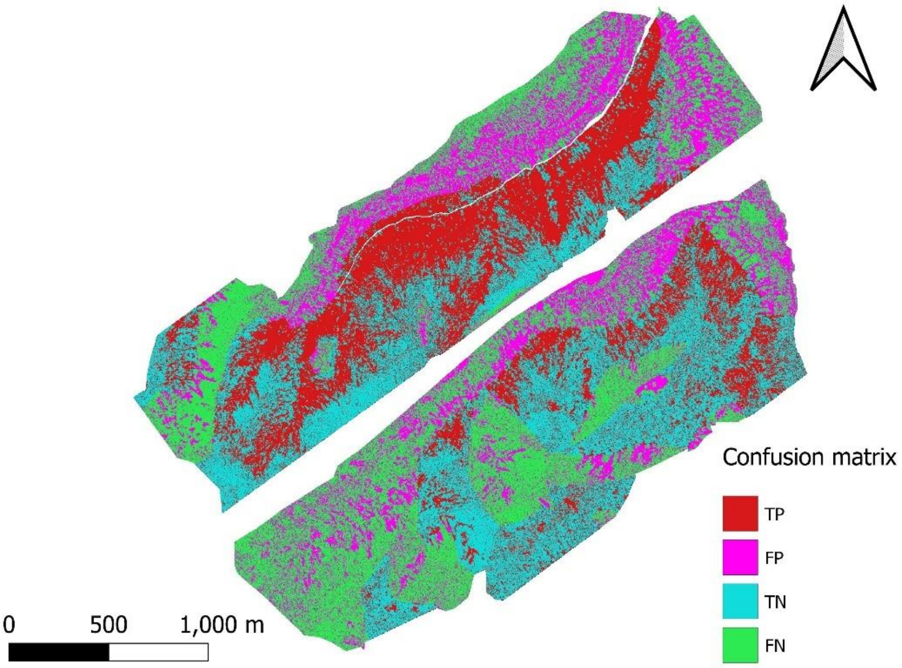

Figure 9. Confusion matrix of ALS and ground observed damage in Rakottyás and Pogány-Rózsás valleys. The colours indicate damage detected by both methods (red), by ALS (purple), by ground-based survey (cyan), and by none of the methods (green).

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.

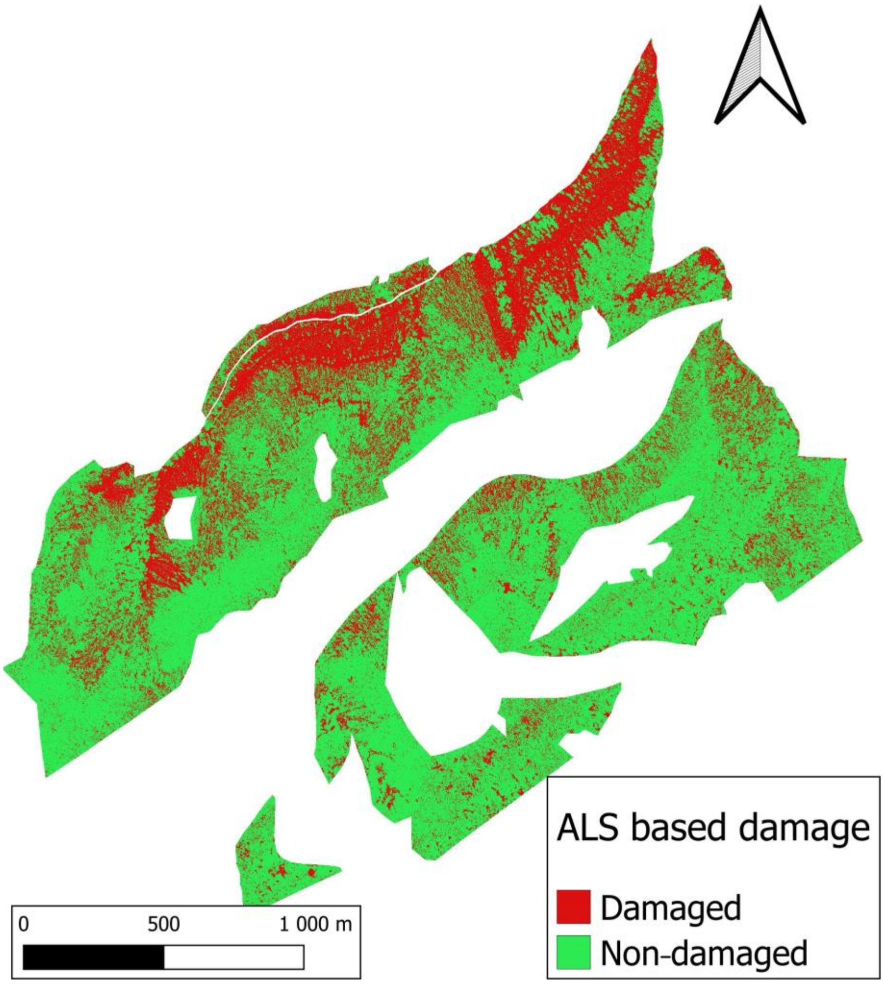

Figure 10. Comparison of two valleys on pixel scale of ALS damage data, where Rakottyás showed significantly more damage (54.35%) than Pogány-Rózsás (36.74%)

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.

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

Norbert HORVÁTH* – Csilla CSIHA

Institute of Wood Technology and Technical Sciences, University of Sopron, Sopron, Hungary

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

* Corresponding author: horvath.norbert@uni-sopron.hu; H-9400 SOPRON, Bajcsy-Zs. u. 4, Hungary

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).

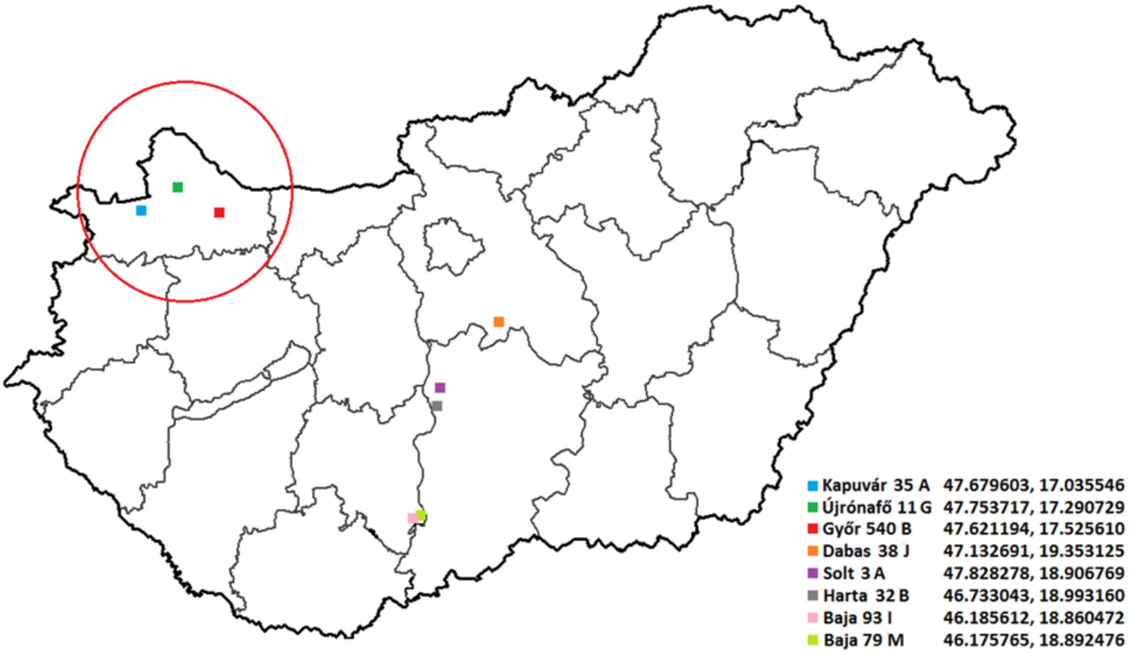

Figure 1. The relevant Pannónia poplar plantations in Győr-Moson-Sopron County (Kapuvár 35 A; Újrónafő 11 G and Győr 540 B)

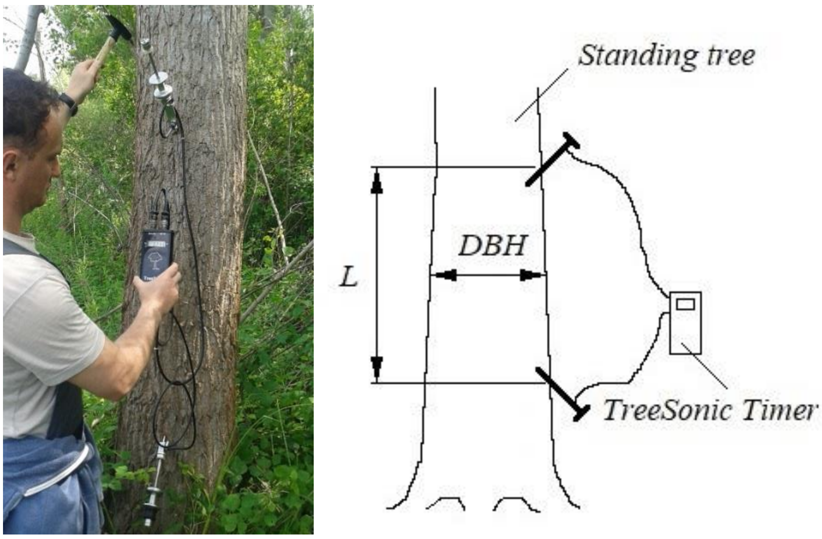

Figure 2. The time-of-flight (TOF) stress wave measurement on trees with a "Fakopp" TreeSonic device (left) and its schematic figure (right).

Fifty trees were investigated ($n_{trees\ tested/site}$=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:

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

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.

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

Jutka NMARNÉ KENDÖL[a*] – Katalin MOLNÁR[b] – Imre BERKI[c] – István FEKETE[d]

[a] Roth Gyula Doctoral School of Forestry and Wildlife Management, University of Sopron, Sopron, Hungary
[b] Benedek Elek Faculty of Pedagogy, University of Sopron, Sopron, Hungary
[c] Faculty of Forestry, University of Sopron, Sopron, Hungary
[d] Amity Institute of Psychology & Allied Sciences, Amity University, Kolkata

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 fahasználat 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 népszerűsítésére, mivel azok szemléletmódosító hatása bebizonyosodott.

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

[*] Corresponding author: kendol.julianna@phd.uni-sopron.hu; H-9400 SOPRON, Ferenczy J. u. 5, Hungary

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).

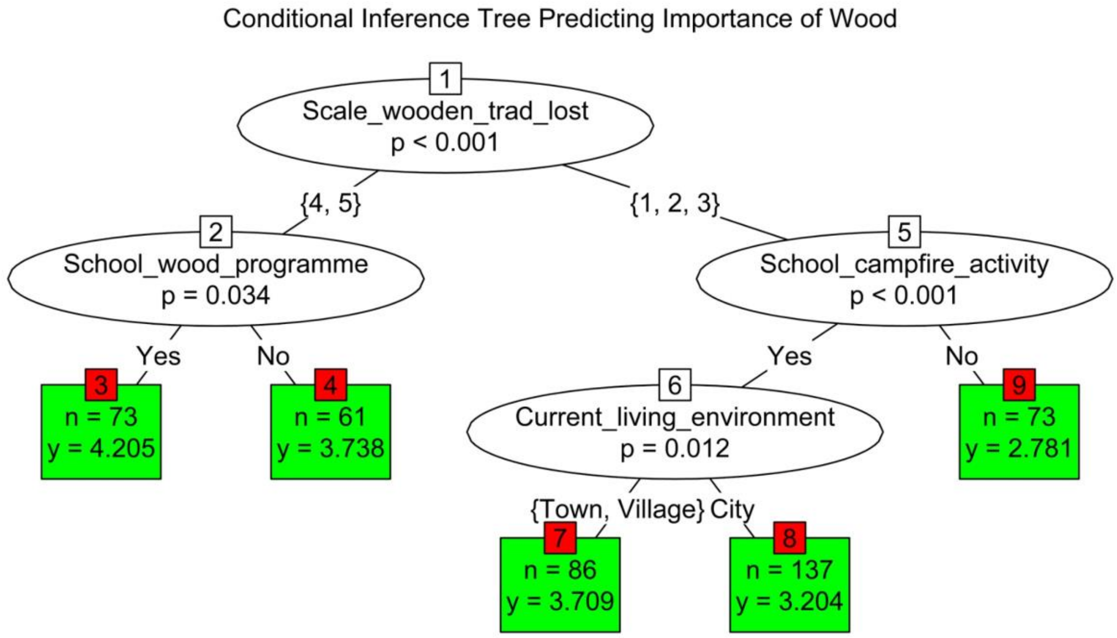

Figure 1. A Conditional Inference Tree structure explaining and predicting the ordinal type of outcome measure "Importance of Wood". Each significant explanatory variable is represented by an oval circle together with the Bonferroni-corrected p-value of the significance test. Classification rules are 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.

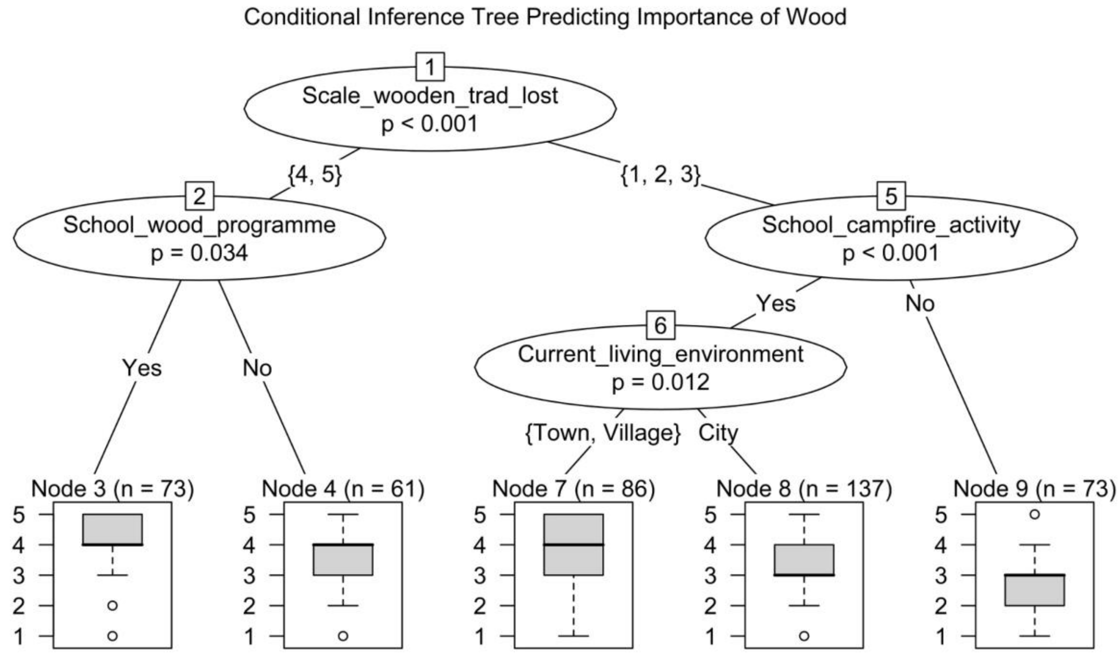

Figure 2. A Conditional Inference Tree structure explaining and predicting the outcome measure "Importance of Wood" with the distributions of responses at the terminal nodes. Oval circles in the representations at the terminal nodes designate outliers. Figure 2 is another representation of Figure 1: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

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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.

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

Bálint HEIL[a*] – Dávid HEILIG[a] – Viktória CSANÁDY[b] – Kinga BERTA[c] – Róbert KURDI[c] – Róbert FEJES[c] – Gábor KOVÁCS[a]

[a] Institute of Environmental Protection and Nature Conservation, Faculty of Forestry, University of Sopron, Sopron, Hungary
[b] Institute of Informatics and Mathematics, Faculty of Wood Engineering and Creative Industries, University of Sopron, Sopron, Hungary
[c] Sustainable Solutions Research Laboratory, University of Pannonia, Veszprém, Hungary

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

[*] Corresponding author: heil.balint@uni-sopron.hu; H-9400 SOPRON, Bajcsy-Zs. u. 4, Hungary

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).

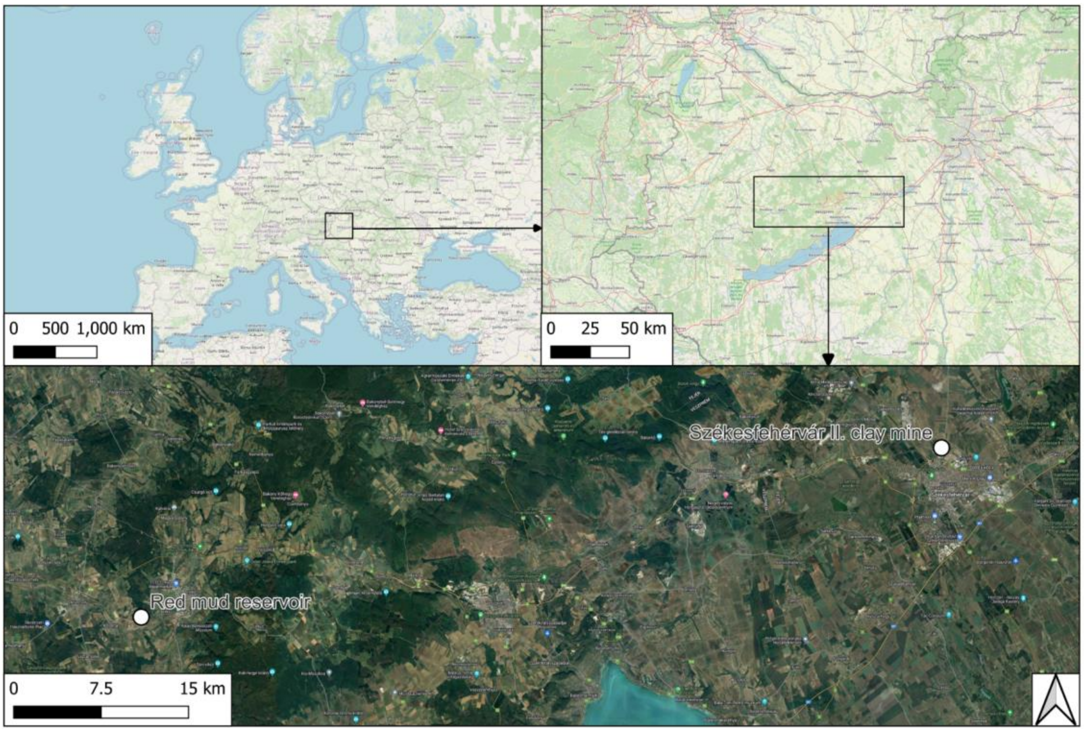

Figure 1. The place of origin of the red mud and the location of the experimental area

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)	6.7[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.

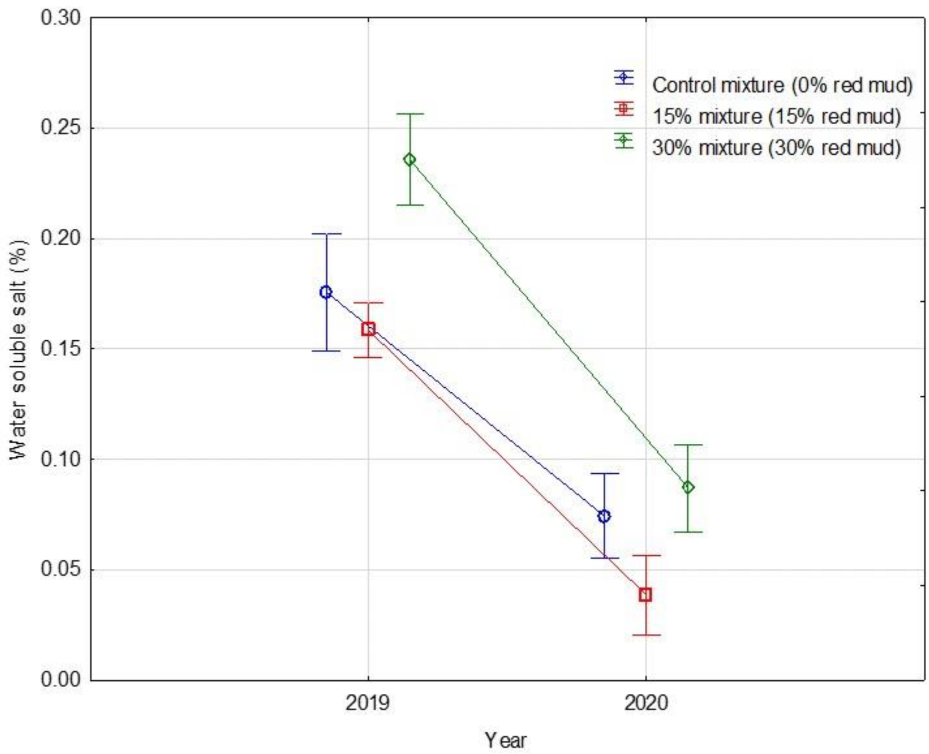

Figure 3. Means and 95% confidence intervals of water-soluble salt contents in the two consecutive years of the open-air pot experiments with red mud treatments.

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.

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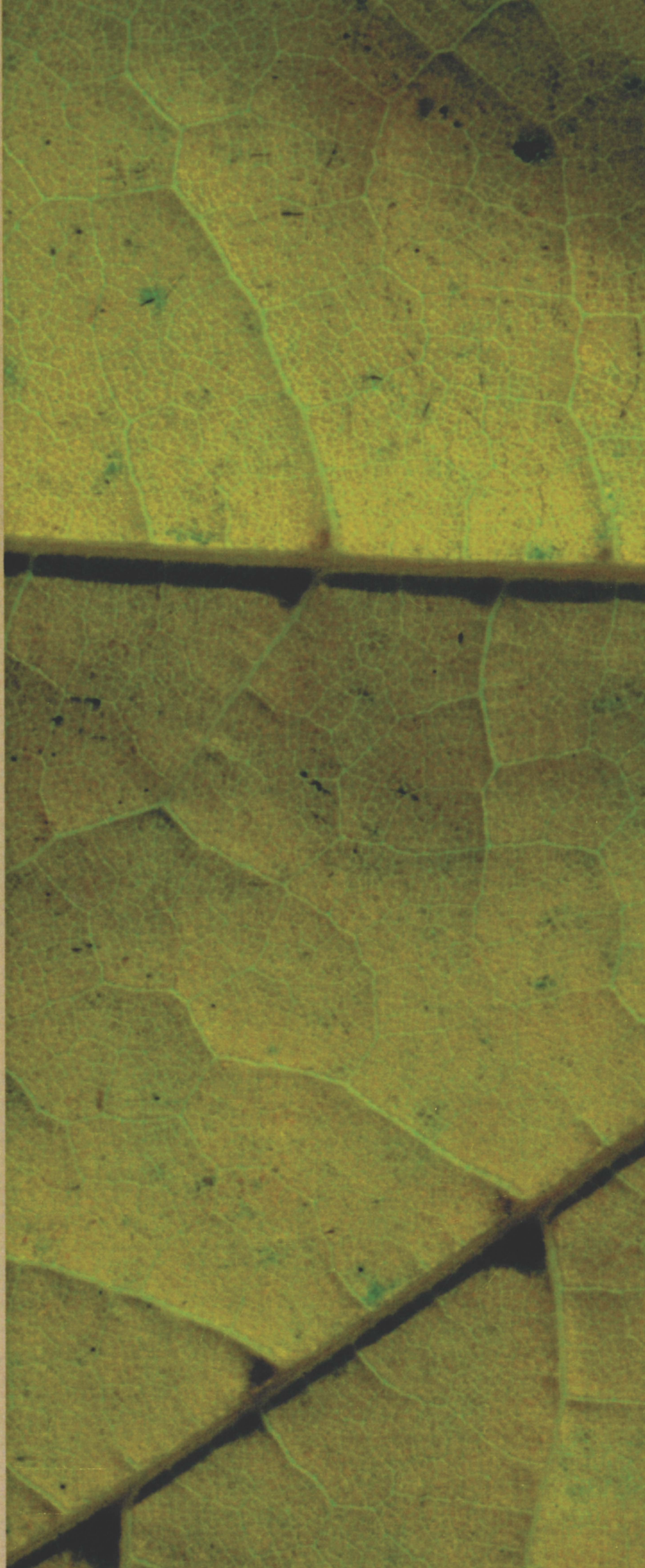

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