Tracing the Holocene distribution of beech and oak forests in the Carpathian Basin using stand-scale paleoecology: the role of land use changes

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Research Period: 2018-2023

1. Introduction of the research topic, our prior knowledge, research questions

Paleoecological techniques document biological change, and provide information useful for reconstruction of 'baseline' conditions prior to recent human influence (Davis et al., 1998; Lindbladh and Bradshaw, 1995; Szabó et al. 2016). In particular, the study of small forest hollow deposits allows the vegetation reconstruction of individual forest parcels over long time periods, most often ranging from today to 1000-11000 years (Bradshaw, 2007). Forest hollows are dominated by pollen, spores, charcoal and plant macrofossils that have travelled only a few meters from source plants and thereby resolve vegetation dynamics at the scale of the woodland stand. Vegetation can be reconstructed with very high spatial resolution that can be easily compared with plot-based surveys of modern vegetation. Hence, stand-scale palynology provides a key link between paleobotanical and contemporary ecological studies (Calcote, 1998).
This research project was building on the advantage of stand-scale pollen studies, their localness and comparability with historical and forestry datasets. Forest hollows are numerous in oceanic areas, particularly in the cool temperate (Köppen: C_{wa}) and boreal climate zone (Köppen: D_{fc}). In this research project we made an attempt to look for small hollow sites in the more humid North East Hungarian Mid-Mountains (Bükk, Mátra and Börzsöny Mts) and in Western Transdanubia, in the Őrség-Vendvidék-Vasvár Region. Given the continental character of the Carpathian basin (Köppen: C_{bfx}, C_{afx}, D_{bfx}), we knew that this will be challenging due to our warm summers with high evaporation rates. Under the continental temperate climate regime, only mid altitude sites were expected to deliver full or at least Late Holocene (<4200 cal yr BP) sediment sequences from forest hollows, and we were also afraid of bioturbation by swindles and discontinuous sediment accumulation restricted to certain part of the Holocene only.
We were particularly interested in the Holocene dynamics of two tree taxa: common beech (*Fagus sylvatica*) and oaks (*Quercus robur, Q. petraea and Q. pubescens*). Beech is an economically important tree species with 26 and 24% cover in the Bükk and Mátra Mountains, and it was assumed that its cover was reduced during the Middle Ages and early modern times due to the overexploitation of its forest stands by coppicing and charcoal production. In addition, we also expected its replacement by oak in many paces due to its better re-sprouting ability and mast production. We expected that its actual distribution in the Hungarian forests does not represent the climate and habitat prescribed niche of the species, but much more the legacy of historical land use (Péch, 1891; Kelemen et al., 2013; Kelemen, 2014a).

Regarding the other target ecosystems, the lowland steppic and mesic oak forests of the Danube-Tisza Interfluve Region, a natural borderline was expected between a landscape with oak forest steppe dominance and a landscape dominated mostly by a mosaic of open and closed Pannonian sand grasslands, wet saline and fen meadows (Biró, 2008; Biró et al., 2015). In this project we planned to analyse 10 remnant oak and 7 remnant poplar forest stands with documented oak (*Quercus robur*, *Q. petraea*) or white poplar (*Populus alba*) dominance since AD 1780. Since the mesic type oak forest stands (Convallario-Quercetum) developed on alluvial soils, the pedoanthracological analysis of at least two under-canopy soil profiles was the primary research method. We also attempted pedoanthracological study in a drier, currently poplar dominated forest stand, even though in these forest stands the humic layer is very thin. In order to compare the stand-scale paleo-vegetation information with the regional vegetation compositional changes, the analysis of two larger sedimentary basins was also planned (Móricz-gát, Lake Kolon, Table 1.1.).

Our aims were:
1. to explore the vegetation dynamics of several forest stands prior to the historically WELL documented time,1900 CE
2. to date the first appearance of beech in these study sites
3. explore the actual herbaceous flora of the forest stands, and list the presence of beech forest indicator understorey elements
4. use DNA metabarcoding studies of soil samples to test the applicability of this method in detecting the former presence of beech in forest stands where the tree cover is currently not beech
5. use pedoantracology and elaborate the technique of wood charcoal analysis to detect stand scale forest compositional changes in the NE Hungarian Mid-Mountains
6. train a new expert (Gabriella Darabos) on anthracology.

We seek answer to the following questions:
(1) Was the areal cover and altitudinal distribution of beech forests larger prior to the onset of Late Iron Age and Medieval forest clearances and prior to the Industrial Revolution?
(2) How did the herbaceous flora change in the studied regions?
(3) How did past forest management influence the biodiversity of the actual forest stands?
(4) Using stand scale palynology, pedoanthracology and metabarcoding DNA studies can we prove the former presence of beech in areas where beech is missing today, but the area is potentially beech covered? When did oak forests appear in the Holocene and how did they survive in the drier parts of the Great Hungarian Plain?

Table 1.1. Study sites with expected number of cores

Study area	Forest hollow sediment (no.)	Soil DNA samples (no.)	Pedoanthracology (no. profiles)	Lake sediment
Börzsöny	-	12	3	-
Mátra	2 (Kőris-bog, Pisztrángos-bog)	10	1	1 (Lake Fekete)
Bükk	2	10	-	-
Őrség-Vendvidék-Vasvár	2	-	-	-
Kiskunság	1	-	3	2 (Móricz-gát, Lake Kolon)

Completed research tasks by year

1 September 2018 –31 August 2019

According to the original work plan our tasks were the soil sampling for DNA metabarcoding analyses in the Bükk and Mátra Mountains, the pedoantracological study in 1 forest stand currently under NOT beech cover (1 of the soil DNA sites), PCR amplification, tagging and sequencing of the soil samples with the trnL primer pair, AMS 14C dating, pollen and plant macrofossil analyses of 2 forest hollows and 1 landslide basin sediment sequence from the Mátra Mountains (Pisztrángos bog, Kőris bog, Lake Fekete), vegetation, floristic and historical forestry document survey in the Mátra and Börzsöny Mountains in the forest stands studied for DNA (32 sampling points) and around the studied forest hollows. In this year we also planned radiometric dating, pollen and diatom analyses of Lake Balaton, C/N and Morphologi grain size parameter measurements of the Lake Balaton sediment sequences. Our plan also included pollen analyses of a 120 cm lake sediment sequence from Lake Kolon in the Kiskunság and vegetation, floristic and historical forestry document survey in the remnant oak and poplar forests of the Kiskunság.

As a first step we conducted the Bükk National Park Authorities in September 2018 and with their help we selected and visited 8 potential forest hollows what we visited in December 2018 (see table below). At each place we did reconnaissance drilling with an Eikelkamp corer and upon returning to the lab tested the sediments for pollen. The only forest hollow where pollen preservation was sufficient is in the vicinity of Egerbakta (Egerbakta Felső-tó and Nagy-tó), where sediment drilling will was carried out later, in the summer of 2021 for high resolution pollen study. In December 2019 Zsuzsanna Pató did soil sampling for DNA metabarcoding analyses in the Bükk Mountains. She collected 10 pulled soil samples from forests that are currently covered by beech, forests where beech is not present at the moment but on the basis of its exposure, mesoclimate and elevation beech was likely present before forest clearance's in the Middle Ages. She also selected 2 sites where beech is not present and we do not expect its earlier presence due to habitat characteristics. Instead of the originally planned PCR amplification, tagging and sequencing of the soil samples (including samples from the Börzsöny, Mátra and Aggtelek), we decided on an easier and quicker technique (real time PCR: qPCR), for which Zsuzsanna did primer planning and testing in 2019, and analysed the soil samples with this primer in 2020. Her main aim was to demonstrate the presence of beech in areas currently covered by oak forests, but where the potential vegetation would be beech forest. We have altogether 120 DNA samples (+controls), as we collected 60 top-soils samples from 30 sites (2 soil-samples/site) and from every samples we performed 2 DNA extraction.

In 2018 and 2019 we completed the pollen and plant macrofossil analyses of Pisztrángos Hollow in the Mátra Hills and wrote up a paper for the journal Holocene (Pató et al., 2021). The main finding of this paper was that in the north facing slope of the Kékes Mount cold boreal forest communities survived into the Holocene with the dominance of Stone Pine, Scots Pine and Norway Spruce, and this community has been replaced by a linden dominated mixed oak forest around 7000 cal yr BP. Beech likely established at this site prior to 3000 cal yr BP. The main inference form this study is that the cold microclimate northern hill of the Kékes has been a long term refugium during the Holocene, and this characteristics of the place will inevitably help the persistence of beech here against global warming.

AMS ^{14}C dating was done in 2019 on the lake sediment of Balaton, Kolon Lake and Móricz gát, the latter two from the Kiskunság.

We completed the grain size analysis of core Tó34F and Tó34a from Lake Balaton, analysed 65 pollen samples from the top meter of the core, and carried out REVEALS based land cover reconstruction for the last 1000 yr. The results of the pollen analyses have been presented at two conferences in 2019 (see publications).

One employment was within the first year of the project: Ferenc Szmorad was employed to do botanical survey around the soil DNA sampling points in the Mátra, Börzsöny and Aggtelek Mts. His report is attached as ESM 1. Apart from providing species lists, he did semi-quantitative estimate of the relative cover of each species.

There are two points in the original work plan that we did not manage to accomplish in the first year of the project, these points have been postponed to 2020. These are the vegetation, floristic and historical forestry document survey in the remnant oak and poplar forests of the Kiskunság and the analysis of the Kolon Lake pollen samples. These samples have been prepared for pollen, the slides await counting.

We also completed the acquisition of a new microscope (OLYMPUS CX31). In addition, we bought a binocular microscope multiplier. The project participants attended 5 conferences and gave 12 talks related to the topic of the project. International collaborations were with Petr Kunes and Magdalena Moskal-Hoyo, who started the teaching of Gabriella Darabos for charcoal based identification of tree species. Gabriella visited Prague in 2020 to study the method from Dr Premysl Bobek (Laboratory of Paleoecology, The Czech Academy of Sciences, Institute of Botany, Prague) and she started analysing the kiln charcoal samples from Aggtelek to reveal whether the original forest cover of the Nagy-fennsík was beech dominated or not. She visit the laboratory of Magdalena Moskal-Hoyo to learn anthracology in 2020.

The group published 13 articles in 2019 where the NKFIH project was acknowledged.

Table 1.1. Potential forest hollows in the Bükk Mts

No.	Forest parcel
1.	Felsőtárkány 47/B
2.	Cserépfalu 14/C
3.	Felsőtárkány 134/A
4.	Bükkzsérc 58/F
5.	Cserépfalu 47/A
6.	Cserépfalu 58/A
7.	Egerbakta 32/VI3
8.	Bátor 23/VI

1 September 2019 –31 August 2020

According to the original work plan our tasks were the drilling, pollen and plant macrofossil analyses of 2 forest hollows from the Bükk Mountains, DNA sequence analyses in ObiTools, vegetation, floristic and historical forestry document survey in the Bükk Mountains and in the Őrség/Vendvidék region in the forest stands studied for DNA and around the studied forest hollows, pollen and diatom analysis of Lake Balaton, C/N and Morphologi grain size analysis of the Lake Balaton sediment sequence, selection of 3 Kiskunság remnant forests for pedoantracological study, vegetation, floristic and historical forestry document survey in the Kiskunság in the forest stands and lakes studied for pollen and macrocharcoal, and extension of the historical forestry document survey to the pollen catchment areas of the studied lakes/mires, data interpretation and writing of papers

According to our work plan, the major task of the 2020 year was the sediment sampling of the Bükk Mountain forest hollows (Egerbakta lakes) selected for analysis on the basis of the 2019 reconnaissance survey. The major limitation of our planned work was the complete lockdown of the university with the coronavirus outbreak that did not allow for the researchers to undertake fieldwork between March-September 2020. We arranged all paperwork with the National Park authorities and postponed the drillings for 2021. Given the limitation of fieldwork possibilities an extension of the project was required by 1 year. However, in 2020 we concentrated on the analysis of the existing sediment cores from Lake Balaton, Lake Kolon (Kiskunság) and Lake Fekete (Galya-tető, Mátra) and continued the DNA metabarcoding and Fagus primer development work.

Lake Fekete is situated at 730 m asl in the Mátra Hills. The lake is surrounded by beech forest today. Our main research aim was to determine the expansion time of common beech (*Fagus sylvatica*) at this location. In 2020 58 samples were analysed for pollen, 93 layers for organic content (loss on ignition analysis) and 20 samples were studied for plant macrofossils. The age model of this record is based on 8 AMS ^{14}C ages that suggest the formation of the lake basin ~8300-8500 years ago. Beech expanded at the site from 4730 cal yr BP (Fig. 1) and replaced mainly lime (*Tilia* sp.), and we also demonstrated its continuous presence at low population density since the formation of the lake. These results are the first for the Pre-Carpathian Hills that demonstrate relatively late expansion of beech at 700 m a.s.l. compared to other mid elevation sites in the North Hungarian Hills (usually 6500 cal BP at 300 m asl). We also proved continuous presence and thus nativeness of Norway spruce (*Picea abies*) in the Mátra Hills. A major outcome was the demonstration of vertical movement of the vegetation zones in the Mátra Hills during the Holocene with an Atlantic phase oak-lime forest dominance. A similar forest type is found in the east sector of the European broad-leaved forests around the Volga River today. Oak and lime are dominant here with a significant proportion of elm (*Ulmus glabra*). The presence of a similar forest type in the Mid-Holocene at 730 m in the Mátra Hills suggests cold winter continental climate with warmer than present summers. It is also obvious that beech expansion was climatically controlled in the Mátra Hills, and took place when winter temperatures increased to reach the tolerance limit of beech (around -5 oC). The publication of these results is in progress. The results have already been presented at the Annual Meeting of the Hungarian Palaeontological Society and will be presented at the Hungarian Ecological Congress in 2021. The work is combined with a database building that collects all pollen records from the region where *Fagus sylvatica* was detected in the Holocene. The database will be made available to the public online, and is currently used for another paper that compares *Fagus* distribution models under different climate scenarios in the Holocene in the Carpathian region and in the future using the MPI global climate model and its regional submodel RegCM with scenario RCP8.5 (Pieczka et al., 2017, 2019; Torma et al., 2008, 2011). Using the predictive ecological modelling of Boosted Regression Trees, we made our predictions for the reference period 1970-2000 CE, and then for 2070-2099 CE. The model suggests a remarkable decrease in beech population by the end of the 21st century, both in the RegCM region and in Hungary. The potential areas with the highest chance for persistence are in the Alps and Carpathians, while the most important domestic areas are the Bakony, Mátra and most importantly the Bükk Mts. These results (Pécsi, 2020) were written up in a master thesis and are currently under publication in conjunction with the fossil database.

The study of Lake Balaton cores Tó34f and Tó34a continued in 2020. The former is a short core covering the last 1000 yr. For this core pollen analysis was completed, sediment chemistry and C.N analyses were also completed in 2020. In addition, the sediment samples were also analysed for chironomids in order to see how human impact, particularly fish farming, lake level changes and terrestrial land use influenced aquatic biodiversity. The results are promising (demonstrate strong dependence of the aquatic fauna on fish predation), and are currently under publication by PhD student Zoltán Szabó and Ivett Pálfi. Pollen analysis of the long core (Tó 34a) also continued. So far altogether 65 pollen samples were counted from the two cores and these analyses suggest that *Fagus sylvatica* mass expansion took place in the wide region of Lake Balaton at 135 cm (4460 cal yr BP) that is comparable to the date obtained in the Mátra Hills. On this sediment core high resolution micro XRF measurements, XRD and TEM, δ^{18}O and δ^{13}C analyses were made by Ivett Pálfi in scope of her PhD that focused on the biogenic carbonate precipitation and analysed the ratio of Calcite – Mg calcite – protodolomite and the crystal structure of these compounds. Together with the XRF and δ^{18}O, δ^{13}C d18O data these analyses came to several very important conclusions. Just to mention here one: two evaporative periods were clearly demonstrated in the lake's 16.5 ka old history: at 8100 and 5500 cal yr BP, when summer lake levels decreased and lake water evaporation reached all time maximum for 1-2 centauries. The interpretation of the rapid climate change events in a European context is in progress, and the first manuscript presenting these results is also underway.

The DNA work focused on the newly developed beech primer application for the soil DNA extracts. Using real time PCR we were interested in whether we can demonstrate beech presence in forest stands where beech is not present today. The test successfully demonstrated the presence of beech DNA in soil samples where beech is the main canopy tree today, but failed to demonstrate beech presence in cases where beech is not present today but its former presence is possible. This suggests that the applied primer works well for modern DNA, but fails to amplify beech DNA in fossil situation. Zuszanna Pató, who is the chief scientist in this subject is currently writing up a short methods paper with these results. The paper focuses on the primer development. She also applied the beech primer pair in sediment samples from Lake St Anne, where beech pollen and plant macrofossils were both present, and obtained negative result further supporting DNA degradation is the main reason for DNA amplification failure. Nonetheless, the primer pair has very high fidelity to beech, which is a great achievement.

We also contacted and obtained quotation from the Genome Analyzer Service for ITS and trnL metagenome analysis of the soil DNA extracts, and we eventually decided to send for metabarcoding (Illumina sequencing and PCR amplification) 48 DNA extracts in 2021.

Regarding the soil charcoal analyses, Gabriella Darabos continued the work on the Aggtelek charcoal and lime piles. As described in the 2019 report, Gabriella planned two short visits to Prague and Krakow to master herself in anthropology (wood charcoal analysis), but these visits had to be postponed due to the coronavirus outbreak. This also meant that she made limited progress with the analyses. So far two kiln samples have been analysed and they suggest the dominance of lime (Tilia sp.) and European hornbeam (Carpinus betulus) on the Aggtelek Plateaus, beech charcoal was not yet recovered. She will continue the work in 2021.

Floristic survey in the Bükk Hills was completed by Ferenc Szmorad, but the Őrség region vegetation survey was postponed to 2021.

1 September 2020 – 31 August 2021
According to the original work plan our tasks were the d*rilling, AMS 14C dating, pollen and plant macrofossil analysis of 2 forest hollows from the Őrség/Vendvidék/Vasvár Region, writing of papers on the DNA metabarcoding results and forest hollow pollen and vegetation surveys in the Mátra, Börzsöny and Bükk Mountains, vegetation, floristic and historical forestry document survey in the Őrség/Vendvidék/Vasvár Region around the forest hollow, pollen analysis of Móricz-gát mire in the Kiskunság, AMS radiocarbon dating, historical forestry document survey in the Kiskunság in the forest stands and lakes studied for pollen and macrocharcoal, and extension of the historical forestry document survey to the pollen catchment areas of the studied lakes/mires, quantitative land cover reconstruction on the basis of the Holocene pollen record of 2 large sites in the Kiskunság*

The scientific work in 2021 followed the work plan. First of all, we finished the pollen, plant macrofossil, organic content and geochemical analyses of Lake Fekete (Gaya-tető, Mátra Hill) and using all proxy results presented our results at the Annual Meeting of Hungarian Palaeontologists and at the Hungarian Ecological Congress in 2021. The preparation of the manuscript using these results was finished and the manuscript was submitted to the journal Holocene in December 2021 (D1) with a title "Holocene expansion of beech in the Carpathian Basin: mysterious presence followed by Late Holocene mass expansion". This manuscript combines the results of Lake Fekete with a large number of regional pollen and plant macrofossil records and also includes distribution modelling of Fagus sylvatica in East-Central Europe (last 11 kyr and projections to 2100). The paper also discusses the causes of late expansion and the expected future role of beech in near-natural forest communities in the Carpathian Area.
In 2021 we (Tibor Standovár, Ferenc Szmorad, Enikő Magyari) also managed to obtain two new sediment cores from a small lake and a forest hollow site in the Bükk Mts. With the help of the Bükk National Park, Lake Egerbakta was sampled in July. Several 2.5-3.4 m long sediment cores were obtained using a Livingstone piston corer operated from a platform and the pollen, macrocharcoal, organic content and chemical analyses of the cores has started in August 2021. Two new international PhD students joined the project in 2020, both work on these sediment cores. Tekle Gurgenidze completed the macrocharcoal analyses by December 2021, her PhD focuses on the Holocene fire history of Hungary, while Abigail Amponsaah Ofosu-Brakoh is currently analysing the deeper sediment for pollen and other physico-chemical proxies. Preliminary results suggest that at the elevation of the lake (~280 m) *Fagus sylvatica* was already established at the formation of the lake, but oak (*Quercus*) species were dominant. The lake was used for hemp retting in the Medieval times, and this results extreme pollen concentration of hemp (*Cannabis sativa*) pollen in the pollen record. Radiocarbon dating of the site is in progress, but the pollen record suggest that we likely face a young formation time (probably 2-3 thousand years). In December 2021 we returned and sampled the forest hollow (Egerbakta Upper Lake). An 80 cm core was retrieved and it analysis is also in progress for all proxies.
In the Kiskunság sand region our main research question is the lowland limit of oak distribution in the Holocene. Together with Tamás Rédei we visited in 2021 (May - August) 4 forest stands in the vicinity of Csévharaszt that were not deforested in the last 3 centuries according to historical maps and the forest herb flora. We dug 2 m deep holes and collected soil samples for pedoanthacological analysis. Here we would like to test the former tree species composition of the forest. The soil samples were analysed by Gabriella Darabos, we found tiny charcoal in most layers, however their species identification using wood anatomy was not possible (even with the help of well-trained Czech scientists), therefore we focus on the soil macrofossil (seeds, twigs) content that is currently analysed by Máté Merkl and Gabriella Darabos. Our aim is to date the soil profiles using 14C dating and provide a successional series of the herb and tree vegetation in the Northern Kiskunság Region.
The pollen and geochemical study of Lake Balaton was completed in 2021, and together with Ivett Pálfi 2 manuscripts are under writing at the moment. The first focuses on the history of beech and land cover changes in Transdanubia based on the Lake Balaton pollen record that is amended by other pollen records from Transdanubia. The second paper reconstructs available Holocene climate changes in Transdanubia using Ca and Mg-calcite and $\delta^{18}O$ changes in the Holocene sediment of Lake Balaton.
In 2022 the plan is to finish the work plan of the project by doing the lake sampling in the Vendvidék Region and analysing these cores as well.

1 September 2020 – 31 August 2022
According to the original work plan our tasks were the data interpretation and writing of papers.
In this year we focused on the investigation of the Egerbakta Big Lake sediment cores taken in the summer of 2021. High resolution pollen analysis was conducted on 47 samples, MP-AES measurements of 63 samples was used to examine changes in the chemical composition of the samples and altogether 25 ^{14}C and ^{210}Pb measurements were done on the sediment core to provide an absolute chronology. These results were first presented in 2022 at the Hungarian Environmental Science Conference in Cluj Napoca by Eniko Magyari, the full results will presented by Abigail Ofosu in 2023 at the INQUA Congress.
Our results show that the sediment extends back to ~1600 cal yr BP; the lake is much younger than expected. We detected beach pollen (*Fagus sylvatica*) in all samples (5-10%), but given the young age of the sediment, we did not manage to capture the time when beech expanded in the Holocene in this area. Unexpectedly, however, we found an extreme amount of hemp (*Cannabis sativa*) pollen in the sediment, and our age-depth modelling suggests that hemp pollen increased in the sediment around 600 AD, which is the time of Slav and Avar expansion in the region. We demonstrated hemp retting between 600 and 1850 AD, suggesting that this area was an important hemp fibre producing zone. Currently, using these results in combination with other dated Holocene pollen records where hemp retting was also evidenced (Kismohos, Lake Vaja, Red Lake in Aggtelek) we are writing a publication on the history of hemp retting in Hungary and its impact on the forests in NE Hungary (Ofosu et al.: Late Iron Age and Medieval hemp retting in East-Central Europe. Vegetation history and Archaeobotany in prep.)
We also continued the investigation on Holocene beech expansion and the impact of medieval land use on beech cover in the Aggtelek karst region, where in March 2022 we collected charcoal samples from 32 medieval kiln sites (boksa) at Haragistya and the Sinpetri-Szögligeti plateau in the Nagy-Háló Valley. Gabriella Darabos conducted athracological analysis on 32 localities using 5 litre charcoal samples from each kiln. Using quantitative charcoal counting she calculated relative abundance of the major forest forming

trees for the medieval coppice/charcoal production management period. These were then compared with forest inventory data made at the same localities by Tibor Standovar and Ferenc Szmorad in 2016. Our results are currently being written up for a Q1 publication in Forest Ecology and Management (Darabos et al. Consequences of medieval wood-charcoal production on woodland composition in the beech woodlands (Melitti-Fagetum) of the Pre-Carpathian foothills: prospects for beech survival under the warming climate scenarios). Our results show different behaviour of the forests. We distinguished 6 groups, of which groups 1-3 had had high (40-95%) Fagus representation in the charcoal assemblages. These forest stands today are all characterised by increased representation of *Carpinus betulus* suggesting that these stands are recovering from the medieval land use; they go through a regeneration phase (secondary succession) and with time we expect the recurring dominance of *Fagus* with *Quercus*-codominance in these forests. We also identified a group of forest stands (group 4), where *Quercus* dominates today. These stands were characterise by even higher *Quercus* dominance in the past suggesting that their regeneration trajectory is in the direction of oak dominance; they represent the zonal Pannonian-Balcanic - Quercus cerris-Quercus petraea woodlands (Quercetum petraeae-cerris). We also identified two groups (5-6) in which *Fagus* representation since the Medieval exploitation has increased considerably repressing the formerly dominant *Carpinus*. These stands are the oldest stands in which the charcoal production was likely very intensive in the past, but they had been abandoned long enough to recover. Their character is mixed with *Fagus-Quercus-Carpinus* dominance. Overall, our results only partially confirm the higher representation of beech at the potential beech forest habitats during the Medieval period in the Aggtelek Karst Region. We clearly demonstrate forest stands in which (group 1-2) in which this is the case, but we also find reverse situation in beech habitats. Our conclusion is that this reflects differences in the intensity of medieval forest exploitation. We also conclude that in this region beech has been already supressed in the forests likely earlier, during the Iron Age and Migration period. We summarize evidence for these pre-medieval impacts and conclude that despite the ongoing global warming, the in the west and north facing slopes of the Aggtelek Karst Region Melitti-Fagetum forests have good regeneration potential, forestry should not aim at replacing beech with other species here.

In 2022 the OTKA research team also continued the work on Lake Balaton. Eniko Magyari and Ilona Pál analysed the full Holocene section of core To34f (102 samples), and using the age depth model determined that beech expansion in Transdanubia started at 8000 cal yr BP. After the first maximum, beech declined at 6500 cal yr BP, then increased again at 4800 cal yr BP. The results of this study will be incorporated in a summary paper we currently work on. This paper is focusing on the Holocene expansion history of beech using a large number of pollen records from Hungary, Slovenia, Austria, Czech Republic, Slovakia, Ukraine, Romania and Serbia. In this paper we compare the climate model based Holocene representation of beech with the fossil data based expansion history, examine the reasons of lagged *Fagus* expansion in the Eastern Carpathians, and explain the climatic reasons of early beech expansion in the SW sector of the examined region. This paper will be published in the Journal of Biogeography.

Finally, we also continued our work in the Kiskunság Region, where our main interest is the lowland forest limit of oak. Since Holocene pollen bearing sediments are rare in this region, we (Magyari Enikő, Rédei Tamás, Darabos Gabriella) developed working relationship with archaeologists of the Katona József Museum in Kecskemét, who collected for us soil samples from the pits, defence ditches, fireplaces, wells and houses of prehistoric and historic sites. Gabriella Darabos is examining the charcoal material recovered from these samples. This attempt is still in its infancy, but our results point to the presence of *Quercus*, *Populus*, *Fraxinus* and *Salix* in the medieval monastery of Bugac; *Salix* and *Quercus* in the Sarmatian village of Szentkirály. We will continue these analyses in Neolithic and several Sarmatian settlements of the Kiskunság region to collect enough data for a scientific paper. Our preliminary result suggest that oak forests were present in the vicinity of Bugac even during the Medieval period.

In 2022 more than seven conference presentations and 14 WOS/SCI papers were published in which the support of the NKFIH project is mentioned.

2. The main results of the research

In the Mátra Hills two forest hollows were analysed for pollen and plant macrofossils with this project: Pisztrángos Lake (Nagy-forrás forest hollow) and Fekete Lake. Kőris–mire has been cored, but not analysed yet.

2.1. Pisztrángos lake, Nagy Forrás forest hollow, Mátra Hills stand-scale forest compositional changes

Main findings on the basis of Pató et al. (2020).

Nagy-forrás forest hollow (685 m a.s.l., 0.1 ha, Fig. 2.1.) is located in the Mátra Mountains, on the north facing slope of Kékes (1014 m a.s.l.).

We carried out detailed pollen, conifer stomata and plant macrofossil analyses, as well as radiocarbon dating to examine Late Glacial and Holocene dynamics of vegetation development.

The site dates back to ca. 15,500 cal yr BP (Table 2.1.), when open boreal forests and wet tundra-like habitats occurred around the hollow (Figs 2.2. & 2.3.). Closed forest cover developed around 14,600 cal yr BP, when a boreal European larch-Swiss stone pine (*Larix decidua-Pinus cembra*) forest surrounded the hollow. This vegetation type remained stable up to 7700 cal yr BP. We observed a hiatus between 7700 and 2710 cal yr BP, followed by a beech (*Fagus sylvatica*) dominated mixed temperate deciduous forest.

Our results confirmed that the area was covered by a primary forest, as human influence was visible only from 175 cal yr BP. The relatively long lasting persistence of *Pinus cembra* in the Holocene at relatively low altitude was documented, which has never been found in Holocene sediments in the Pre-Carpathians before. We hypothesize that the north facing slope acted as a cold-stage refugium in the Early Holocene and could play the same role for the present-day beech forest that is threatened by recent climate change.

Figure 2.1. Location of Nagy-forrás forest hollow in the Carpathian Basin and in the Mátra Mountains

Table 1 Results of the AMS ^{14}C measurements from Nagy-forrás forest hollow (core PM-1)

Laboratory code	Dated material	Depth (cm)	^{14}C age years BP	Calibrated age years BP	Remarks
DeA-15374	Deciduous leaf fragments	16	1 ± 27	−27 ± 15	
DeA-15375	Deciduous leaf fragments	36	174 ± 27	148 ± 122	
DeA-13965	*Fagus sylvatica* budscales and twigs, *Rubus* seed	64	2826 ± 25	2928 ± 33	
DeA-16685	*Fagus sylvatica* twigs	72	2503 ± 20	2612 ± 81	
DeA-15378	*Larix* and *Pinus cembra* needles	76	6918 ± 39	7753 ± 44	
DeA-13966	Woods, twigs, *Quercus* and *Pinus* budscales	84	4821 ± 30	5547 ± 48	outlier
DeA-15379	Conifer needles	100	11211 ± 52	13111 ± 107	
DeA-16686	*Fagus sylvatica* budscales	107-109	2640 ± 21	2762 ± 7	outlier
DeA-15376	Conifer needles	116	11480 ± 46	13389 ± 121	
DeA-15377	Conifer needles	174	12013 ± 48	13991 ± 202	
DeA-13967	*Larix* needle, conifer budscales, moss remains, *Juncus* seeds	229	5445 ± 36	6254 ± 32	outlier

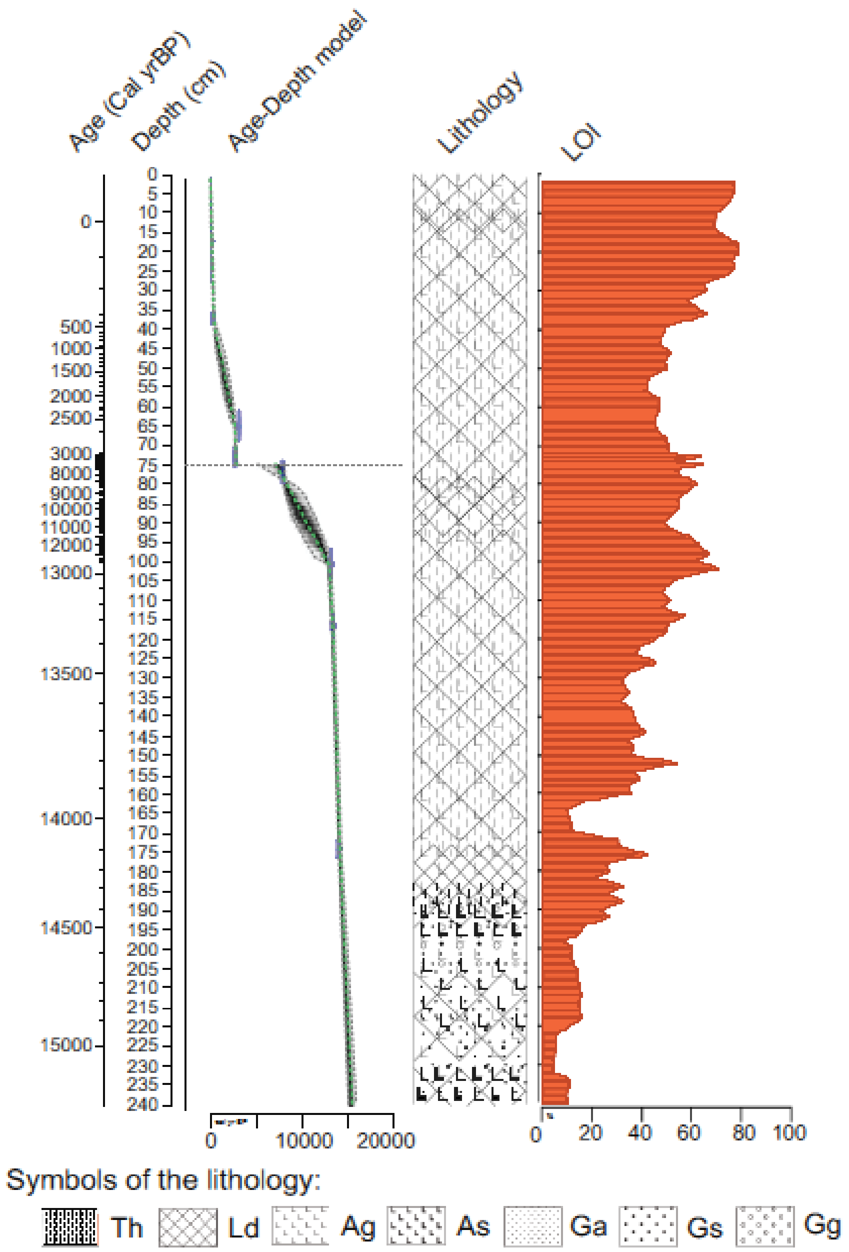

Figure 2.2. The results of age-depth modelling, lithostratigraphical description and loss on ignition measurements of the Nagy-forrás forest hollow, core PM-1. The symbols of the lithography follow the Troels-Smith nomenclature: Th-Turfa herbacea, Ld-Limus humosus, Ag-Argilla granosa, As-Argilla steatodes, Ga-Grana arenosa, Gs-Grana saburralia, Gg-Grana glaerosa (min)

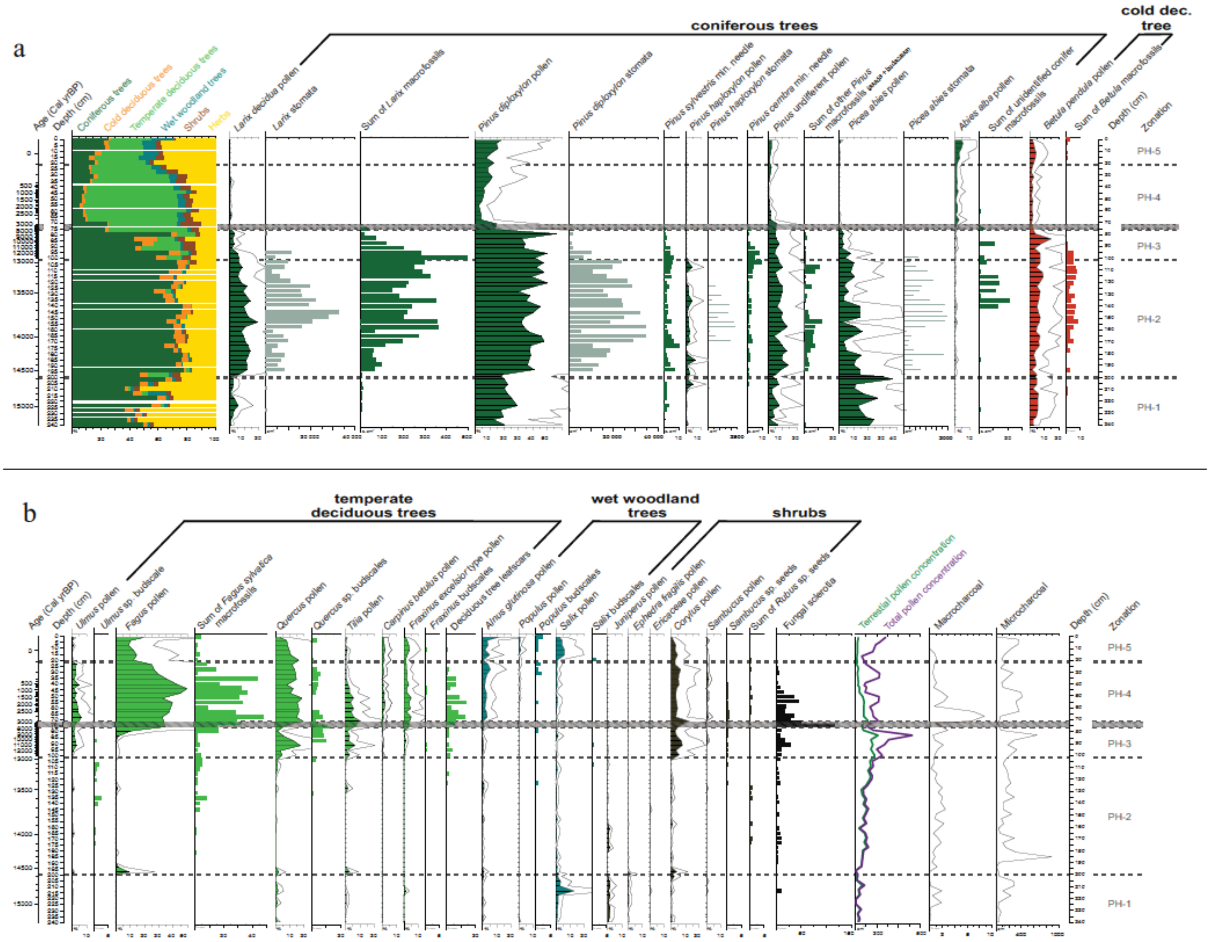

Figure 2.3. Pollen percentage diagrams of selected tree and shrub pollen types and concentration diagrams of the selected plant macrofossils. (a) Coniferous trees and cold-tolerant deciduous trees. (b) Temperate deciduous trees, wet woodland trees and shrubs. The stacked bar chart shows the relative proportion of the different vegetation types (based on pollen record). Filled line charts represent the pollen proportions in percentage, where 100% is the sum of all terrestrial taxa (see total terrestrial pollen), the exaggeration factor (black line) was 3. Grey bar charts: stomata concentrations (pieces in 1 cm^3). Bar charts: macrofossil concentrations (pieces in 5 cm^3). Line charts: the total pollen concentration (in 1 cm^3) and charcoal records

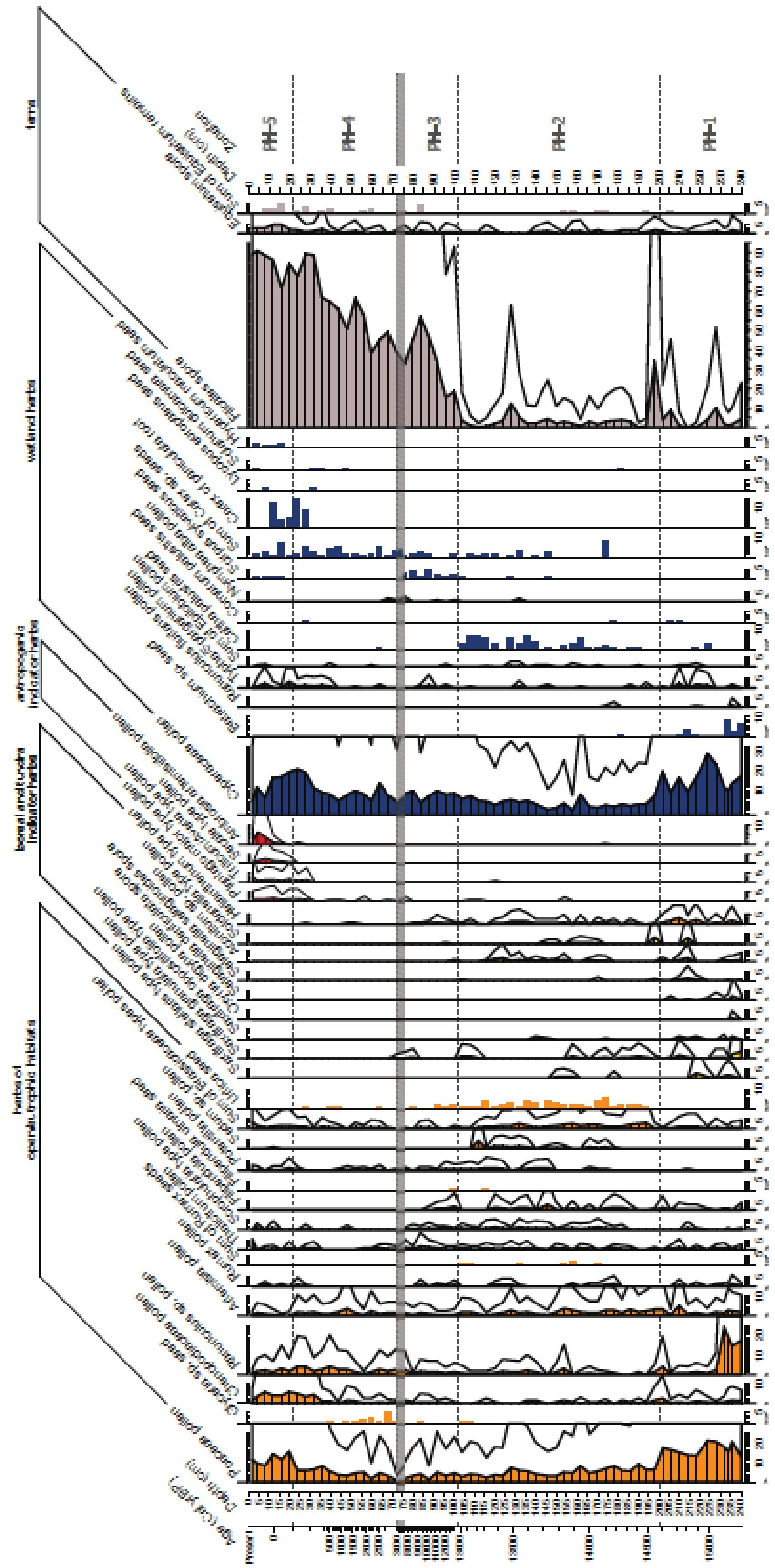

Figure 5 Pollen percentage diagram of selected herb pollen types and concentration diagrams of selected plant macrofossils. Filled line charts represent the pollen proportions in percentage, where 100% is the sum of all terrestrial taxa (see total terrestrial pollen), the exaggeration factor (black line) was 3. Bar charts: macrofossil remains concentrations (pieces in 5 cm^3)

2.2. Fekete Lake, Mátra Hills, Holocene stand scale forest compositional changes

In order to understand the Holocene behaviour of beech in its dry distribution limit, we have done a multi-proxy palaeoecological study on sediment cores from this forest hollow site that can reflect stand-scale changes in forest composition in the Mátra Hills (730m a.s.l., Fig. 2.4.). Our aim was to study the former distribution of beech. High-resolution pollen analysis and plant macrofossil analyses, in conjunction with ^{210}Pb, ^{14}C, ^{137}Cs dating, and organic content analyses were used to date the expansion time and study the driving forces behind beech expansion in the middle Holocene and examine the effects of past land management practices on its modern-day elevation range shifts.

Figure 2.4. Aerial photo of Fekete lake (730 m, left) and up-close shot of Fekete lake

A 415-cm core was collected from the Black Lake (Fekete Lake) in February 2018, and stored at 4°C until further analyses. Pollen analysis was done at 4 cm resolution for Fekete Lake. Plant macrofossil analysis was done on 78 samples.

Pollen & macrofossil analyses showed oak-lime-elm (*Quercus*-*Tilia*-*Ulmus*) dominance with lime (*Tilia* sp.) growing further from the lake edge between 8750-7800 cal BP. Increase in Monocot undiff. macrofossils was coincident with Poaceae increase at ~ 5200 cal BP. The pollen record showed mass expansion of beech (*Fagus sylvatica*) from 4800 cal BP, plant macrofossils suggested its lakeshore dominance from 3500 cal BP. The aquatic succession suggested water-depth increase at *Fagus* expansion, forest fire and drought directly before *Fagus* expansion (Figs 2.5.-2.9.).

Comparing this record with other records in the region, we concluded that beech rapidly expanded and replaced the oak-elm-lime forest belt at low elevation and also occupied the lower part of the spruce forest zone from 4800 cal BP. The largest Holocene fire event preceded the expansion of beech in the mid mountains, showing that the expansion of a new species was aided by disturbance. Later occurrence (from 3250 cal BP) of forest fires in the Mátra Hills led to a decrease in beech population between 3200-2200 cal BP. The decreasing trend halted at ~1800 cal BP following the decline in fire activity and beech saw an increase again. These fire events were connected to Late Bronze Age and Early Iron Age local settlement and hillfort constructions. Comparing our result from the Pre/Carpathian Hills with the North Carpathian mid/Holocene forest changes reconstructed by Lestienne et al. (2022), we conclude that 4500-4800 cal BP marks an interval when beech replaced spruce and mixed oak forests between 1076 m and 730 m a.sl. forming a forest belt that pushed down the oak forest zone and up the spruce forest zone. Available moisture and winter temperature increase together with forest disturbance at the 5.2 kyr cal BP rapid climate change (RCC) event helped the expansion of beech.

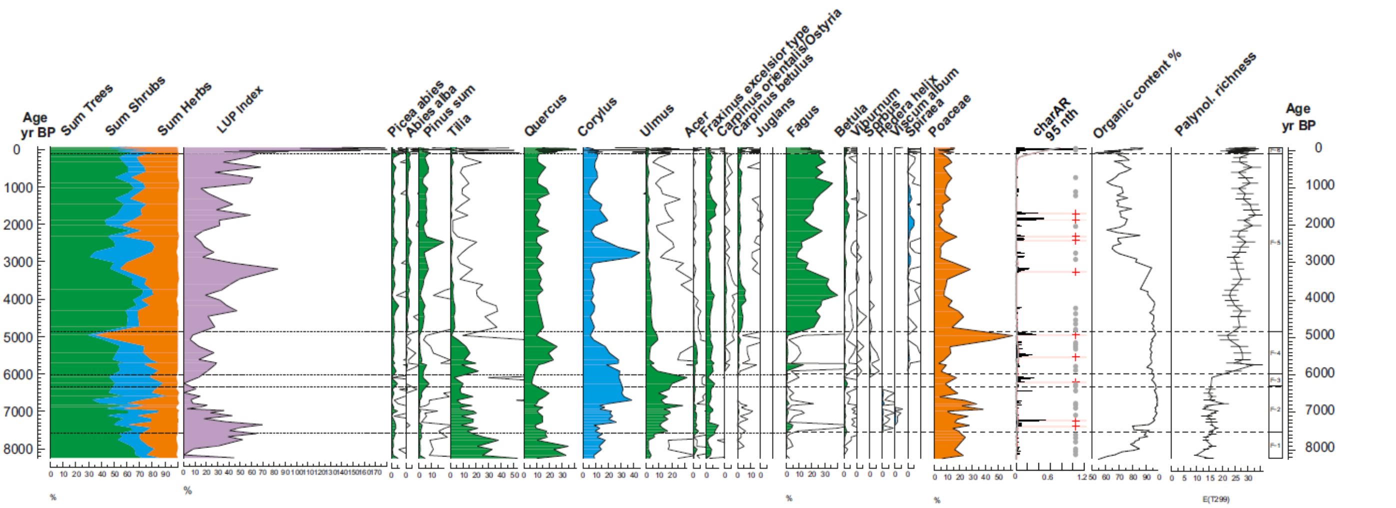

Figure 2.5. Fekete Lake pollen percentage diagram of selected taxa, Land Use Indicator Pollen, LOI, macro-charcoal acc. rates and palynological richness Fig. 4b. Fekete Lake combined pollen percentage and macorfossil diagram of woody taxa

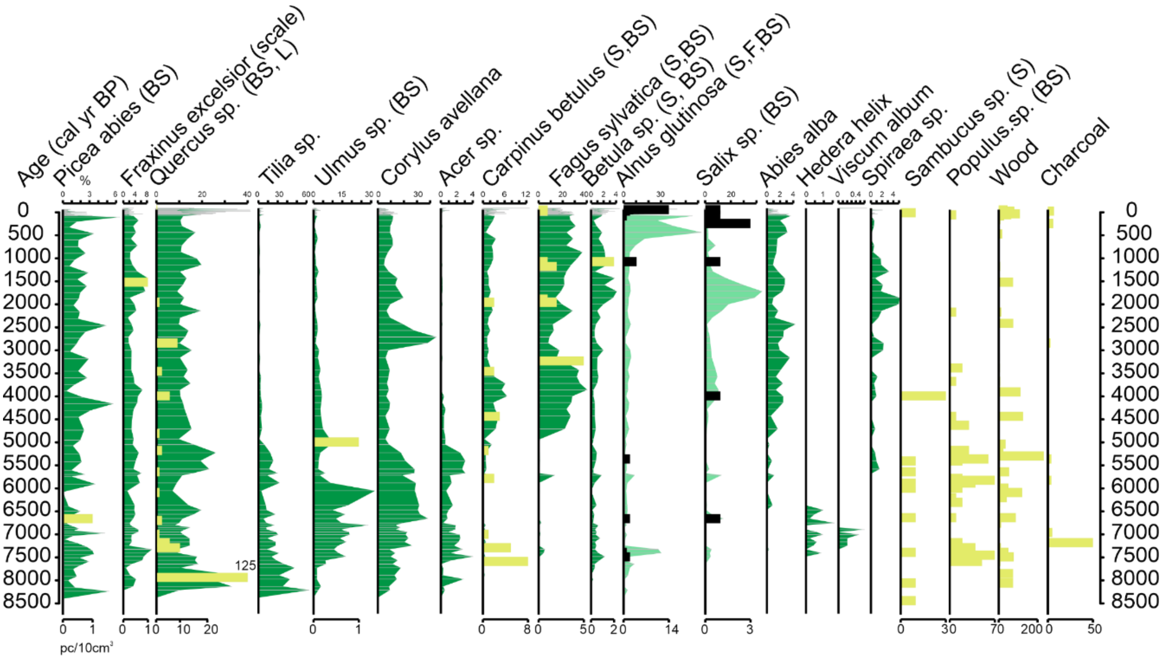

Figure 2.6. Fekete Lake combined pollen percentage and macorfossil diagram of woody taxa

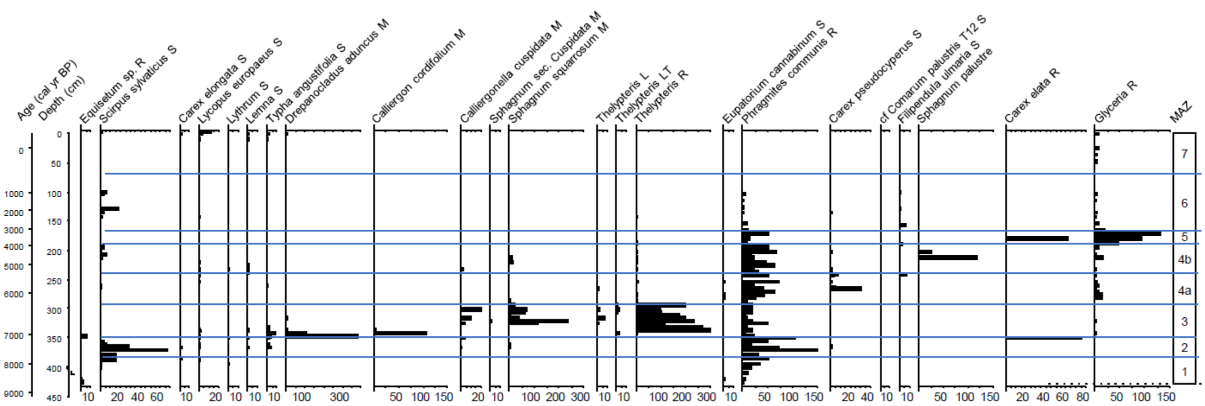

Figure 2.7. Fekete Lake plant macro-fossil record of wetland taxa

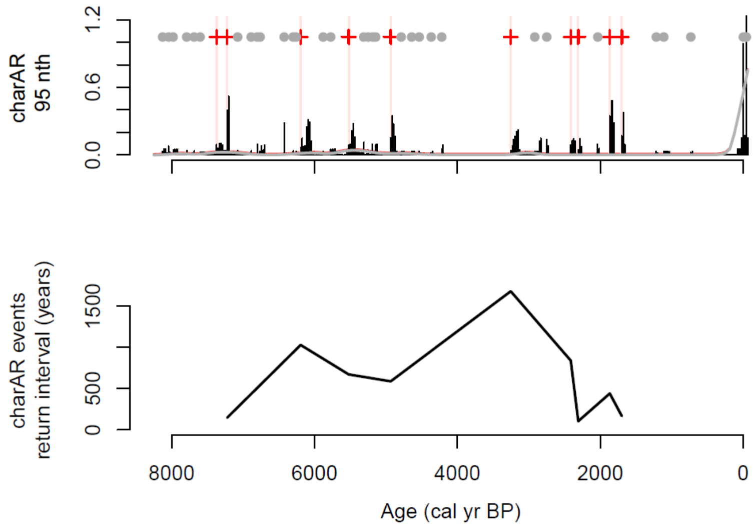

Figure 2.8. Fekete Lake fire history reconstruction based on macro-charcoal analysis, fire events and fire return interval

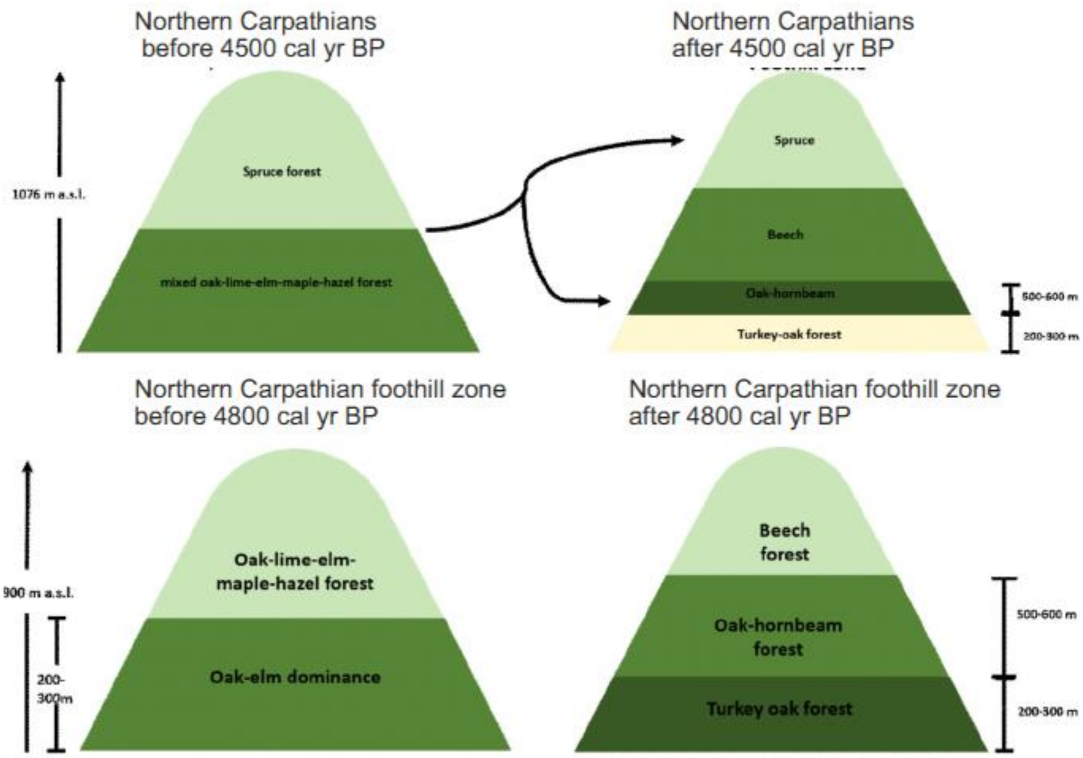

Figure 2.9. Mid-Holocene beech (*Fagus sylvatica*) expansion, altitudinal ranges taken over by beech in the foothill and mountain zone of the Northern Carpathians

2.3. Egerbakta Lake (Bükk Mts)

Our attempt to find forest hollows in the formerly potentially beech covered regions of the Bükk Mts (between 400-900 m) with reasonable pollen preservation failed despite our repeated attempts. We found however the Egerbakta lakes at an altitude of 280 m. We took several 360 cm long sediment cores from one of these lakes, Egerbakta Big Lake (Fig. 2.10.). Pollen analysis was done at a 2-4cm resolution on the best quality core. In addition, loss-on-ignition, major and trace element analyses and macrocharcoal analyses were done on this core. Dating of the sediment was via $^{210}Pb/^{137}Cs$ and AMS ^{14}C. Our aim was to date the sediment, examine if beech has been present locally at this altitude and reconstruct the Holocene local forest succession.

Beech (*Fagus sylvatica*) is not dominant at this site today at 280 m a.s.l., and the site only dates back to 100 BCE (~2100 cal yr BP, Fig. 2.11.). According to the pollen diagram, the lakeshore was semi-open during the Sarmation period, around 1900-2100 cal yr BP (50 BCE – 150 CE), and cereal fields were in the direct vicinity of the lake. The forest was oak (*Quercus*) dominated, like today. Following a short oak forest regeneration period, between 1700 - 1200 cal yr BP (250-750 CE), we see a second deforestation period that affected oak locally. At this time (1200 cal yr BP = 750 CE) hemp (*Cannabis sativa*) pollen started to increase in the sediment and reached 80% by 900 cal BP (1050 CE) suggesting that since the Avar period the lake has been used for hemp retting. We excluded hemp pollen from the main pollen sum, so 80% hemp pollen means that relative to the terrestrial pollen sum hemp pollen reached 80%, which is clearly indicative of its soaking (retting) in the lake, a procedure used for removing pectin and reveal fibres. At the same time wheat (*Triticum*) and rye (*Secale*) pollen also increased together with weed taxa (yellow on Fig.2.10.) suggesting ceral production and grazing in the vicinity of the lake. At the same time, the representation of beech was constant, but low (<3%) suggesting that it has been reduced regionally. This record suggest that hemp retting along with cereal cultivation characterised this area until 300 cal yr BP (1650 CE), when a slow forest recovery started (with oak, beech, hornbeam, birch and alder). The recent willow scrub ring around the lake only developed after the abandonment of hemp retting, in the 20th century. Sediment reworking was also evidenced by the presence of hemp pollen in the surface sediments.

Publication of these results is underway in cope of the PhD work of Ofosu-Brakoh Abigail Amponsaah. The paper concentrates on the history of hemp cultivation in the area of Egerbakta and uses historical information, and comparison with regional pollen records where hemp cultivation and retting was also evidenced.

In connection with the local population history of beech, this site demonstrated that beech has not, or only sporadically been present in the oak dominated forests of this elevation zone (~300 m a.s.l.) during the last 2000 years.

Figure 2.10. Aerial photo of Egerbakta Big Lake (280 m) showing also the piston coring equipment and the process of sediment sampling on the lake in 2021

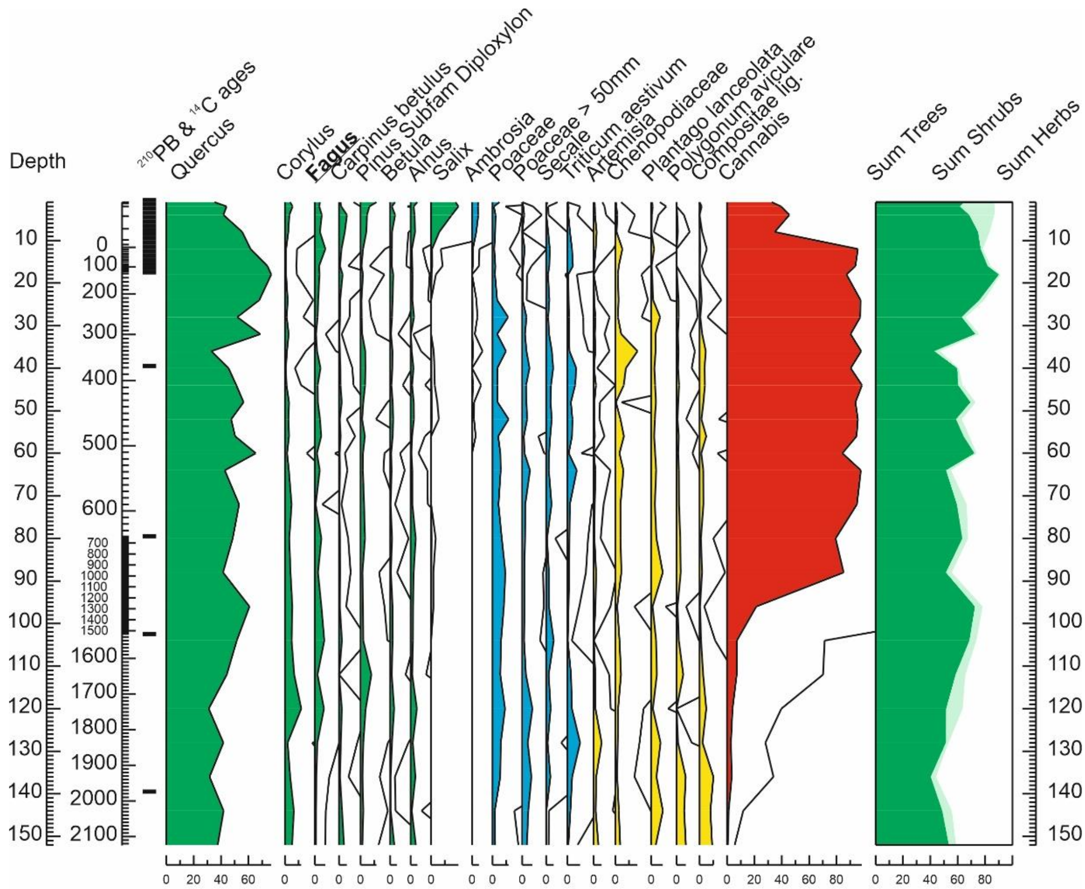

Figure 2.11. Egerbakta pollen percentage diagram of selected terrestrial pollen types. Location of the ^{210}Pb and ^{14}C dates is show non the left along the age scale

2.4. Soil DNA studies in the Mátra Hills

According to the original research plan, our plan was to collect soil samples from different ranges of the North Hungarian mid-mountains, where we have detailed information on the current forest stand composition and potential natural vegetation (Somodi et al., 2017) estimates are also available. Our aim was to do metabarcoding DNA analyses on the soil DNA extracts and using the cp trnl barcoding primer examine the presence of beech (*Fagus sylvatica*) DNA in the soil samples. In scope of the PhD work of Zsuzsanna Pató, a careful site selection was done to include sites that are under beech cover today, sites for which the potential vegetation is beech forest, but today, oak or hornbeam dominates, and sites that are not beech habitats according to the PNV, and are not covered by beech today. We sampled 10 forest stands per mountain range (3 beech, 6 potentially beech, 1 non-beech habitat), and altogether 11 points were sampled in the Börzsöny, 10 in the Mátra and 10 in the Aggtelek hills. We extracted DNA, but simplified the methodology due to the limitation of the trnl primer in telling apart different genera in the Fagaceae family (oak and beech has identical trnl DNA sequences). Instead Zsuzsanna Pató started primer planning and testing combined with ecoPCR. She successfully designed a new primer and tested it on recent material, but failed to demonstrate beech DNA in the soil samples and in Lake St Anne sediments in those cases when the local presence of beech is demonstrated. Unfortunately this part of the project was the least successful, as it did not lead into publication due to the quitting of Zsuzsanna Pató's PhD work. We hope that in the future, in scope of new PhD studentship this work can be completed and with the improvement of the DNA metabarcoding methodology, the carefully stored DNA extracts can be used. Mrs Pató reported her work at the Porto metabarcoding summer school where she got training in the use of the OBITOOL software package.

2.5. Pedoanthracological study in the Aggtelek Hills

Soil charcoal analyses were planned originally in the Aggtelek Hills, where chacoal kilns are abundant, and where medieval forest exploitation for charcoal burning was suspected to have changed the forest composition, which resulted in the repressed representation of beech in habitats that have a typical 'beech climate' (Standovár and Kenderes, 2003; Standovár et al., 2017).

Since charcoal makers cut down all the trees that was available at the time of harvest, and use them without selection, the species/genera spectrum of the wood charcoal records from kilns reflects the species/genera composition of the forest stand at the time of use (Gocel-Chalté et al., 2020). Using this relationship, we collected charcoal from 26 kiln sites (Figure 2.12.) and applied a quantitative method to analyse them (ensuring random sampling).

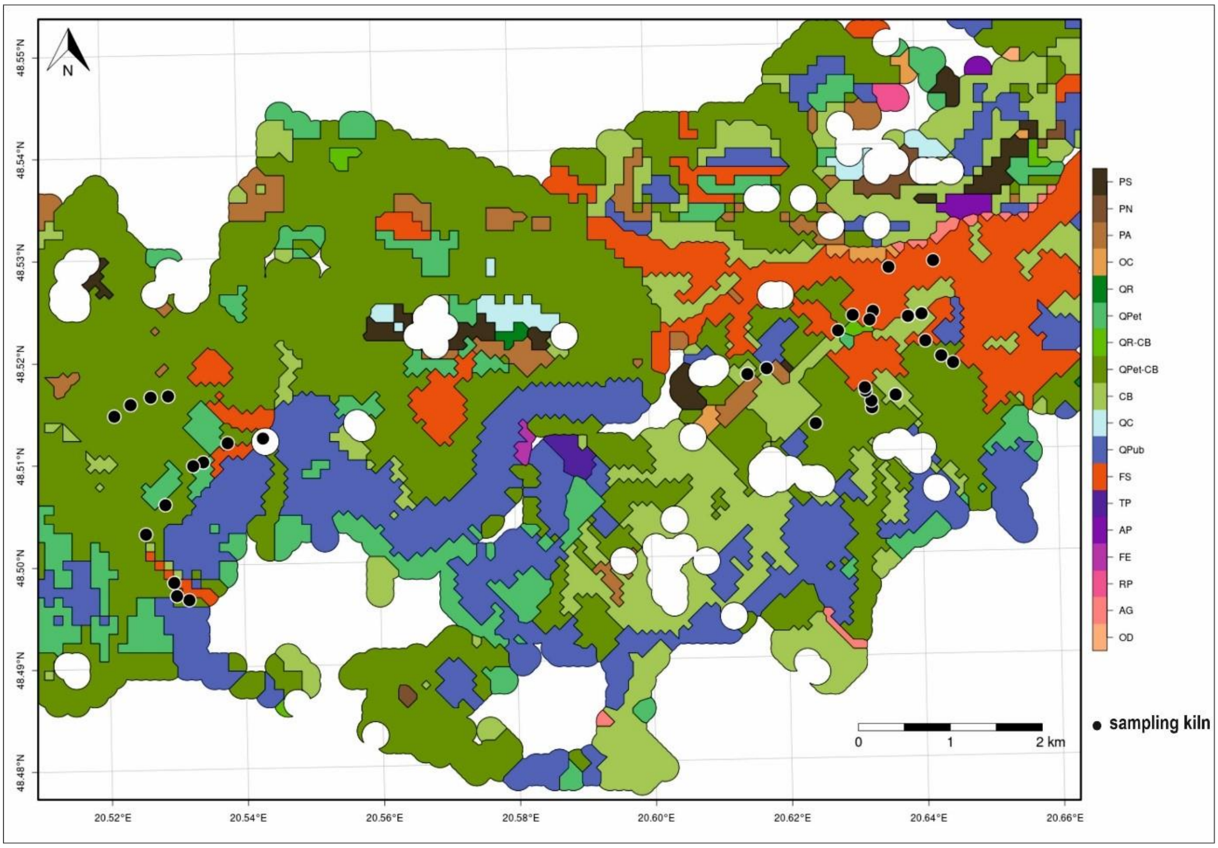

Figure 2.12. Modern vegetation map of the study area with our sampling sites (white circles); abbreviations: RP – black locus forest; FS – beech forest; QC – Turkey oak forest; AG – alder forest; OC – other conifer forest; OD – other deciduous forest; PS – Scots pine forest; PN – black pine forest; QR-CB – pedunculate oak European hornbeam forest; QP-CB – sessile oak – European hornbeam forest; CB – European hornbeam forest; TP – large leaved lime forest; AP – sycamore forest; QR – pedunculate oak forest; QP – sessile oak forest; FE – common ash forest; PA – Norway spruce forest; QP – Downy oak forest)

The comparison of the recent forest stand composition with the charcoal composition is presented on Figure 2.13. This figure shows the relative frequency distribution of charcoal assemblages under the modern forest composition. In most samples, *Fagus*, *Quercus* and *Carpinus* were the dominant charcoal types, and for better clarity, all other tree taxa were grouped under the heading "Other". These include *Acer* spp., *Tilia* spp., *Fraxinus* spp., *Populus* spp., *Salix* spp., *Ulmus* spp., *Alnus* spp., *Prunus* spp., *Betula* pendula and Pomoideae.

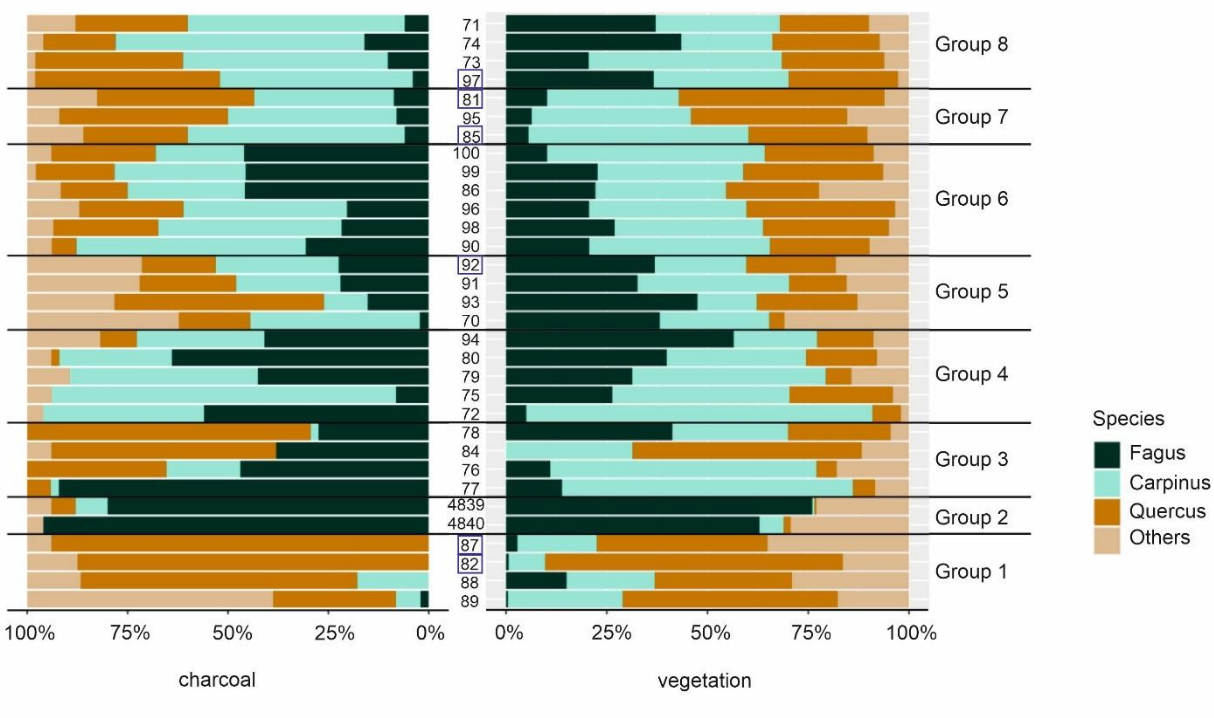

Figure 2.13. Relative frequency distribution of major tree taxa at the kiln sites (a) and in the modern vegetation in 100 m radius of the kiln (b); others include *Acer*, *Tilia*, *Populus*, *Salix*, *Fraxinus*, *Ulmus*, *Prunus*, Pomoideae; horizontal black lines mark the groups defined by Cluster analysis; The numbers squared in blue highlight sampling sites classified as sessile oak-hornbeam forest habitats according to the a priori stand type classification.

This figure indicates that we cannot unequivocally say that beech (*Fagus*) representation was higher at the time of charcoal production in the area. Instead, we see some sites where beech was more abundant in the past (e.g. groups 2, 3), but we also see sites where the reverse is true (e.g. group 6). In some cases, the representation of hornbeam (*Caprinus*) increased in the modern vegetation (groups 1, 3) and in other cases oak become more abundant (group 4). Overall the forest composition trajectories displayed on a heatmap in Figure 2.14. suggest that 1) different stands are in different status regarding secondary succession, out of the 8 groups, in 3 groups beech abundance increased suggesting regeneration, while in one group (6) oak and hornbeam gained abundance and beech decreased suggesting maybe that these forest stands are in different stage of secondary succession and certain habitats are clearly not potentially beech habitats. These non-beech habitats, however, do not fully agree with the a priori classification (squared numbers). Overall, our results suggest that in many places coppice management of the woodland has been given up quite recently (<80 years ago), and the Haragistya and Nagy-Háló Valley areas would not be fully beech dominated without human impact. This conclusion however, does no go against the original assumption of Standovár and Kenderes (2003) and Standovár et al. (2017) that beech representation in the current forest stands is lowered by land use. What our analysis shows, instead, is that this impact has been present since probably the early-mid Medieval times, and by the time of the last charcoal burning (likely early modern age) the forest composition has already been altered and in many places regeneration is on the way. We also demonstrated that charcoal burning was not species-selective. Charcoal burners cut and burnt what was in the proximity of the kilns, the species spectrum was very diverse (13 tree and 4 shrub genera).

These results were already presented at conferences, and currently, a manuscript is under preparation from this study that will be submitted to Forest Ecology and Management (*Darabos, G., Szmorad, F., Standovár, T., Korponai, J., Moskal-Hoyo, M., Bobek, P., Bede-Fazekas, Á., Rédei,* *T., Magyari, E. K. et al. The role of medieval and early modern age land use (charcoal production*) in the current woodland composition of the Pannonian colline beech woodlands). We presented here only a small fraction of the figures of this manuscript here.

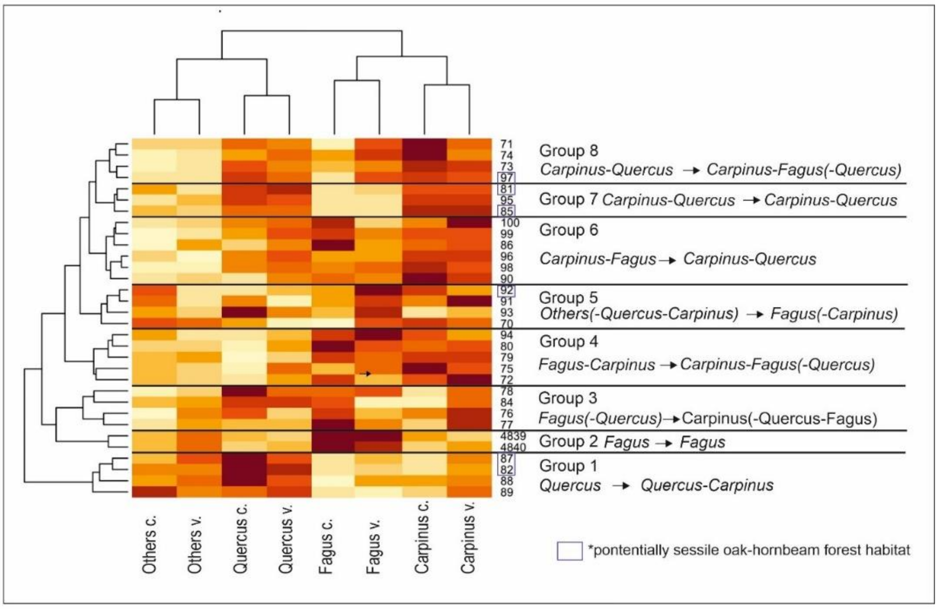

Figure 2.14. Clustered heatmap of the charcoal (c.) and modern tree relative frequency (v.) distribution records; different shades from yellow to dark red indicate low to high relative frequencies of the taxa; the numbers squared in blue indicate sampling sites classified as sessile oak-hornbeam forest habitat according to the a priori stand type classification; on the right of the heatmap the direction of tree compositional change is shown from the past to the present

2.6. Beech expansion and grain size changes in core Tó34a in Lake Balaton

In scope of the OTKA project we did pollen analysis on core Tó34a obtained from the Szemes Basin of Lake Balaton. On this 16500 year old sediment core 16 AMS ^{14}C datings, TOC, TN, ITRAX, MS, grain size, pollen, chironomid and biogenic calcite $\delta^{18}O$, $\delta^{13}C$ were analysed (Fig. 2.15.).

Here we only present a selective pollen records and geochemical results (Figs 2.15-2.17) and concentrate on beech establishment and expansion in Transdanubia. In this region we did not manage to analyse forest hollows for pollen, as all suggested sites proved to be short records with unsatisfactory pollen preservation in the Vasvár Region.

First we demonstrated that Lake Balaton has a pollen source area of 200 km radius, therefore the pollen records presented here give a very much regional picture. At second, our results suggest that beech expansion started after the 8.2 rapid climate change event in Transdanubia, around 7800 cal yr BP when sediment accumulation rates increased in the Szemes basin (Figs. 2.15-2.17.). Beech expansion in Transdanubia preceded the expansion of beech by 1300 years (Kismohos) compared to the Putnok Hills and by 3000 years (Fekete Lake) compared to the Mátra Hills. When we compare this date with the expansion time in the northern part of the Great Hungarian Plain (3100 cal yr BP), then we see that beech expansion took place much earlier in Transdanubia, even though beech was present in the North Hungarian Mid-Mountains as well. This suggests that the Atlantic climate of Trandanubia (likely the Transdanubian mid-Mountain range) differed considerably from the eastern part of the country and this area was the source of the northern and eastern expansion of beech from Slovenia, where beech expanded the earliest.

The Late Holocene history of beech was also studied in two sediment cores in Lake Balaton (Tó 34f and Tó35f). Here we present Tó 35f, which was used for REVEALS modelling to translate pollen frequencies to vegetation abundances in the pollen source are of Lake Balaton (Fig. 2.18.)

These results have been presented at several conferences and partially published. Two manuscripts are listed and are under preparation from these results that are outstanding, as they are the first with independent ^{14}C and ^{210}Pb based chronology.

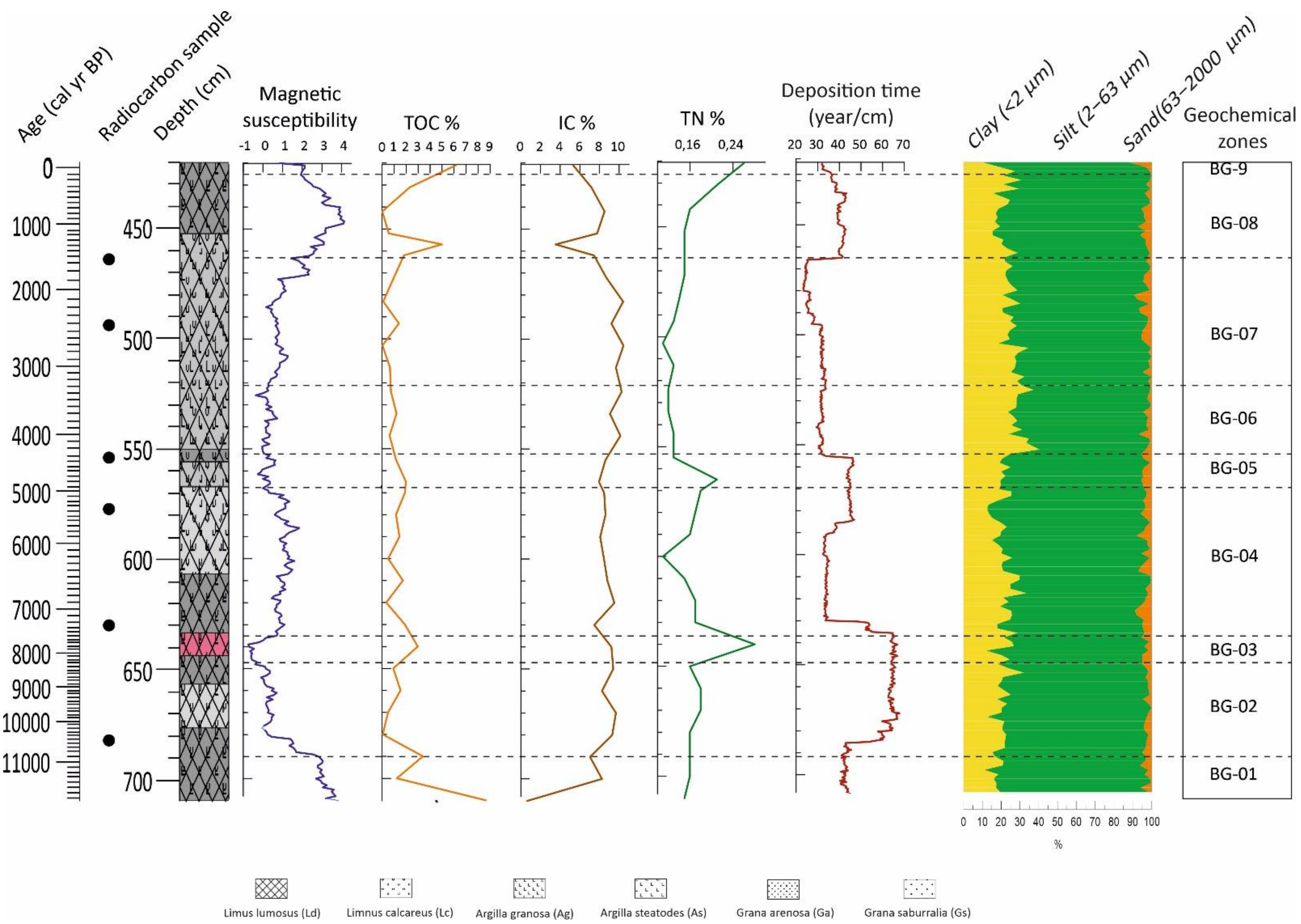

Figure 2.15. Sediment stratigraphy, magnetic susceptibility, total organic and inorganic carbon content, nitrogen content and grain size distribution in Lake Balaton, Szemes Basin, core Tó34a

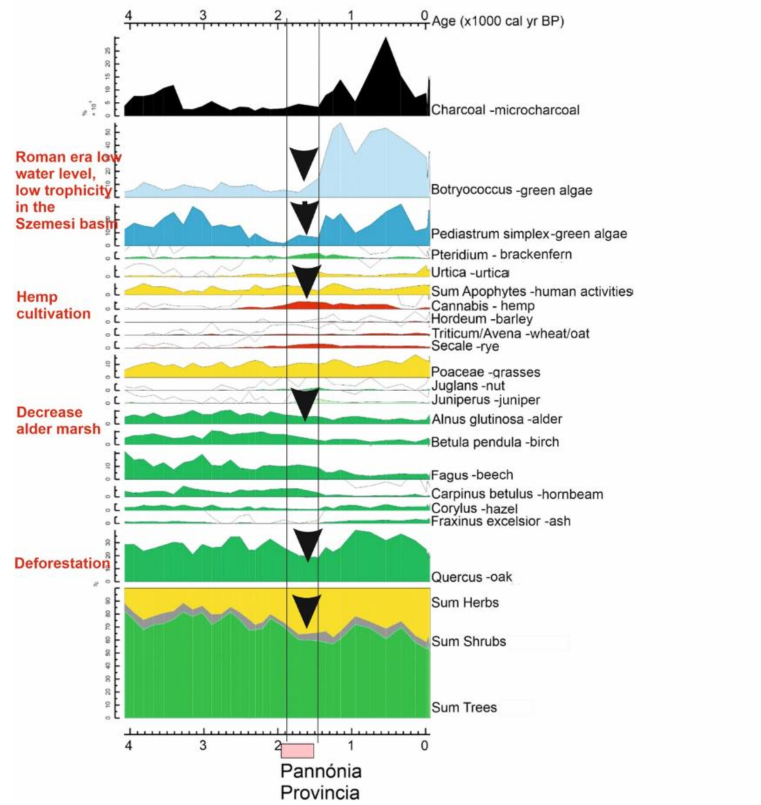

Figure 2.16. Lake Balaton Tó 34a core relative frequency pollen diagram along age (cal yr BP) highlighting the Roman Age human impact

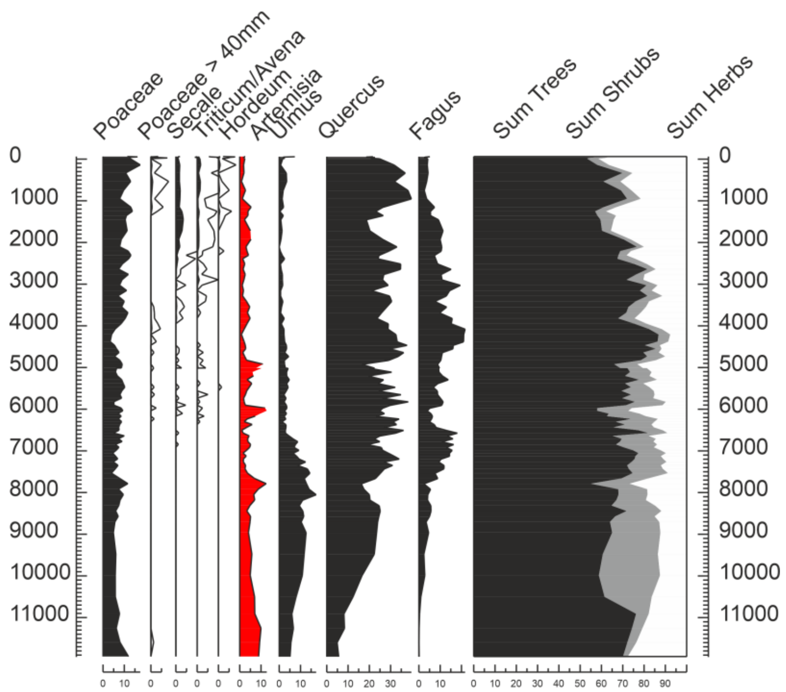

Figure 2.17. Lake Balaton Tó 34a core relative frequency pollen diagram along age (cal yr BP) with selected terrestrial taxa

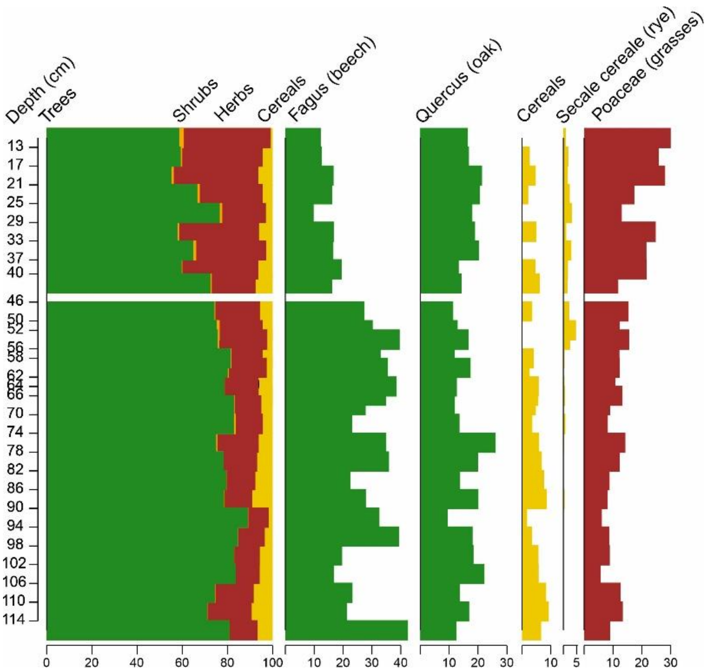

Figure 2.18. Land cover reconstruction using the REVEALS model and PPEs from the Czech Republic, core Tó35a, Szemes Basin, Lake Balaton

2.7. The study of oak lowland distribution limit in the Kiskunság Region

Dr Rédei visited all forest stands with recorded presence of pedunculated oak (*Q. robur*) in the Kiskunság are and made detailed species lists and analysed several relevees to characterise these forest stands. He published these results in 2020 (Rédei et al., 2020). His main finding was that forest specialist species can survive almost only in continuous semi-natural oak forests, that is, in forests that are continuously present and do not undergo any site preparation. This way he demonstrated the continuous presence of oak forest patches in the Kiskunság likely throughout the Holocene.

Our pollen analyses of Kolon Lake and Móricz-gát were only partially successful. As is shown in Table 2.2. the ^{14}C chronology of Móricz-gát suggested that the sediment is likely mixed and does not form a time series. Lake Kolon had mixed pollen preservation, with several sterile layers, the chronology of this sediment sequence is also problematic (Table 2.2.) and at 75 cm it is likely not older than 700 years.

In the Kiskunság oak forests we selected 6 localities for pedoanthrcological study and collected soil profile samples for charcoal analysis. As described in Supplement 1, these large volume soil samples were sieved and screened for charcoal. In some cases charcoal fragments <1 mm were found in large number, but their identification was only successful in two cases (1 *Quercus*, 1 *Carpinus betulus* at 60-80 cm, Csévharaszt) giving little possibility for publishing. In 2022 we changed strategy, and decided to work with archaeologists and collect wood charcoal samples from archaeological sites in the Kiskunság. We made contact with the Katona József Museum in Kecskemét and received samples for analysis from the Sarmatian site at Szentkirály (from wells) and from the Middle Age Village and Cemetary of Bugac (with some Arpadian age samples). As is shown in Supplement 2 and Figure 2.19., the construction material in the Medieval village at Bugac was mainly oak (*Quercus* sp.), with secondary importance of poplar (*Populus* sp.) and ash (*Fraxinus* sp.). Apart from these 3 taxa that likely were abundant in the vicinity of the medieval settlement, as several hundreds of their charcoal were identified, Dr Darabos also demonstrated the presence of beech (*Fagus* sp.) in a burnt medieval house floor (7 pieces), and in one case burnt pieces of a conifer coffin were found, but could not be identified further. The species composition suggest that during the medieval times Bugac was still rich in hardwood and softwood floodplain forests, unlike today. These results have not yet been published. They will be published in collaboration with the museum, and likely in combination with other medieval site charcoal records from the Kiskunság.

Table 2.2. Radiocarbon dates from the sediment core of Móricz-gát and Kolon Lake, Kiskunság, Hungary

AMS C-14 Lab code	HEKAL prep. code	Name/Depth	Material dated	conv. C-14 age (yr BP)	age unc. (1s) +- (y)	Comment
DeA-18726	I/1959/12	Móricz-gát 55 cm	plant and animal remains (>250 μm)	592	25	
DeA-18727	I/1959/13	Móricz-gát 75 cm	plant and animal remains (>250 μm)	316	26	
DeA-18732	I/1960/1	Móricz-gát 95 cm	plant and animal remains (>250 μm)	727	26	C (m/m %) 11.9%
DeA-18733	I/1960/2	Móricz-gát 115 cm	plant and animal remains (>250 μm)	565	28	C (m/m %) 17.2%,
DeA-18887	I/1960/3	Kolon-3 10 cm	plant and animal remains (>250 μm)	-2292	37	0ó.12 mg C
NA	I/1960/4	Kolon-3 30 cm	plant and animal remains (>250 μm)	*NA*	*NA*	0.11 mg C bad quality graphite
DeA-18735	I/1960/6	Kolon-3 55 cm	plant and animal remains (>250 μm)	451	24	1.63 mg C
DeA-18734	I/1960/5	Kolon-3 75 cm	plant and animal remains (>250 μm)	667	27	0.66 mg C

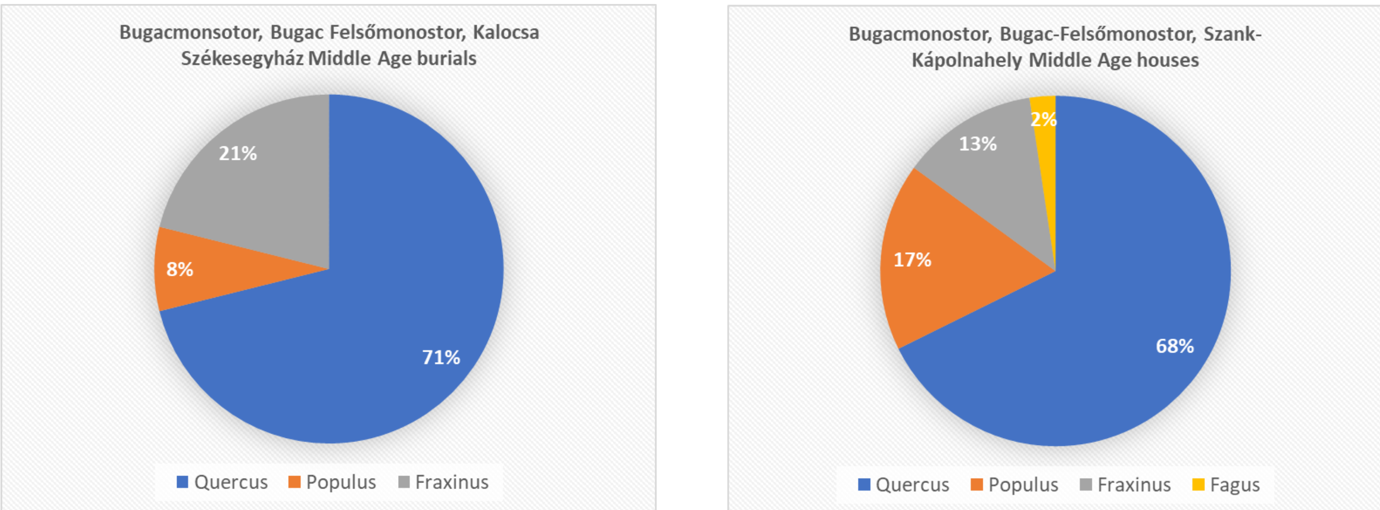

Figure 2.19. Relative frequency distribution of wood taxa in medieval wood charcoal samples from the Kiskunság region, Hungary; on the left 90 charcoal pieces were analysed from 5 medieval burials, while on the right 294 charcoal pieces were analysed from 10 house floor samples; oak (*Quercus* sp., likely pedunculated oak) dominates the charcoal assemblages with poplar (*Populus* sp.) and ash (Fraxinus sp.) being also important

3. Publications on the research topics

During the extended 4 years of the project the research team has published 109 publications, out of which 31 papers in referred journals (mostly Q1 and D1) and dozens of conference abstracts. Most of these papers are connected to the NKFIH project research topics and in the great majority of them the NKFIH project support had been acknowledged.

4. Justification of deviations from the original research plan

As we described above, we had to deviate partially from the original research and work plan in a few cases. As expected, we had problems with finding suitable forest hollow sites in the Börzsöny and Bükk Mts and in the Vasvár region in Transdanubia. We also failed with the DNA metabarcoding study, because of the unsuitability of the original primer and the likely unfortunate long DNA target sequence of the specifically designed Fagus primers. Despite these limitations, the project managed to produce large quantity of valuable data the publishing of which is partially done, and partially currently underway. What we would like to ask is the possibility to complete this report with our current publications on beech expansion history in the Carpathian basin.

5. References

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Supplement 1

CSÉVHARASZT - KISKUNSÁG

Jegyzőkönyv

(Készítette: Darabos Gabriella)

A talajminták gyűjtési időpontja: 2021.06.23. Csévharaszt

A térképek segítségével kiválasztott mintavételi helyeken mintázó gödröket ástunk és a kiválasztott mélységekből kb. 6 kg mennyiségű mintát gyűjtöttünk.

Laboratóriumba szállítás után minden mintából további talajtani vizsgálatok céljára kb. 200-300 g mennyiségeket különítettünk el. Ezt követően a maradék minták tömegének pontos lemérése után a minták iszapolása történt /történik/. Az iszapolás után a szitákon fennmaradt különböző frakciókat szobahőmérsékleten szárítottuk, majd tömegüket is lemértük. (A későbbi elemzés megkönnyítése érdekében választottuk szét az anyagot frakciókra. Néhány esetben a köztes frakció nem mutatkozott olyan jelentősnek, hogy külön válasszuk.) Ezt követően megkezdődött sztereo mikroszkóp alatt minden mintából a faszén darabok kiválogatása. Ezután a mintákból kiválogatott faszén darabok össztömegének meghatározása következik.

TALAJMINTÁK

„Csodanyaras (bolygatott talaj)": mintavételi hely: EOV: 675 895;   213 056

1 minta: MÉG NINCS ISZAPOLVA!

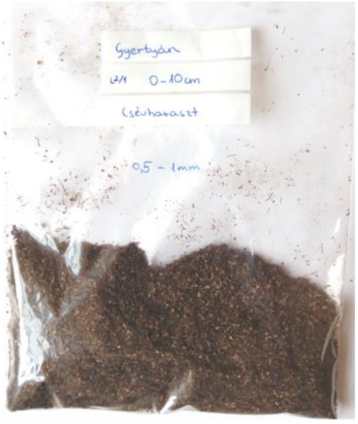
„Gyertyános":

A: Egyik mintavételi hely: EOV:675 604; 213 636

1. minta*: „Gyertyános 2/1" - 0-10 cm*

Össztömeg:**6856,45 g**, ebből iszapolás után feldolgozandó/átnézendő összanyagmennyiség: **133.02 g**

Frakció bontásban: 0,5-1 mm:92,95 g



1-1,5 mm:22,19 g




1,5 mm<:117,88 ,g




A MINTÁBAN VAN FASZÉN!

B:Másik mintavételi hely: EOV: 675 596; 213 653

1. minta: ***„Gyertyános" - 0-30 cm*** **(MÉG NINCS ISZAPOLVA!)**

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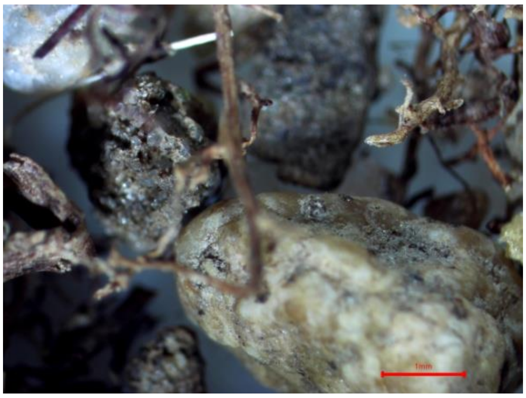
2. minta: ***„Gyertyános" - 30-40 cm***

Össztömeg:**6314,08 g**, ebből iszapolás után feldolgozandó/átnézendő összanyagmennyiség:**129,38 g**

Frakció bontásban: 0,5-1 mm:83,28 g

1-2 mm:27,03 g

2 mm<:19,07 g



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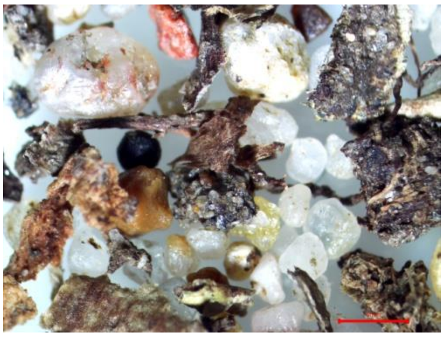
3. minta*: „Gyertyános" - 40-60 cm*

Össztömeg:**6653,96 g**, ebből iszapolás után feldolgozandó/átnézendő összanyagmennyiség:**108,87 g**

Frakció bontásban: 0,5-2 mm:83,01 g



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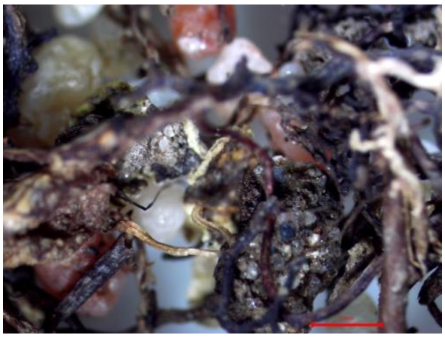
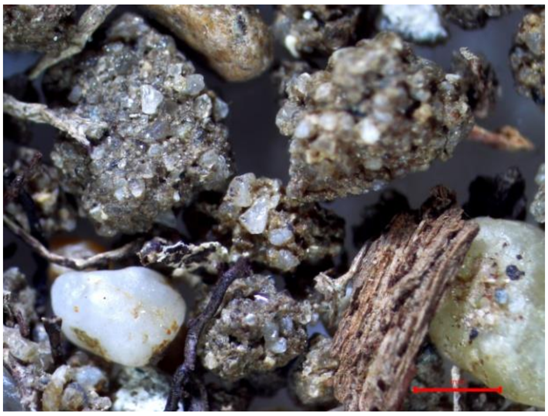
2 mm<:25,86 g



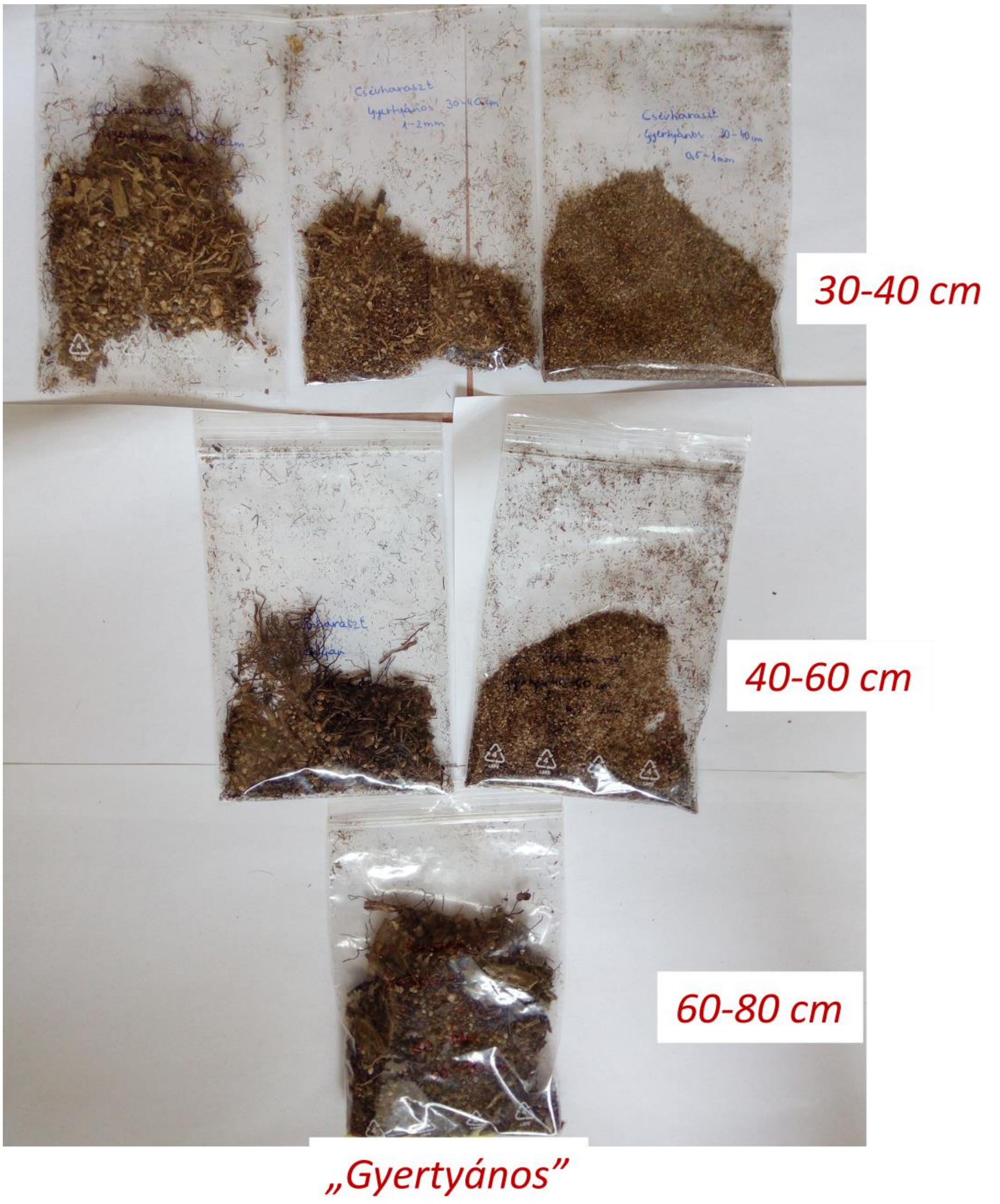
4. minta*: „Gyertyános” - 60-80 cm*

Össztömeg:**6758,78 g**, ebből iszapolás után feldolgozandó/átnézendő összanyagmennyiség:**109,70 g**

Frakció : 0,5 mm< **109,70 g**



A MINTÁBAN VAN FASZÉN!



„Tölgyes 3”:

„Tölgyes 3” (a térképen „CS3”): mintavételi hely: EOV:675 107; 213 905

1. minta*: „Tölgyes 3” - 0-30 cm* (**MÉG NINCS ISZAPOLVA!)**

„Tölgyes 4”:

„Tölgyes 4” (a térképen „CS4”): mintavételi hely: EOV:674 730; 215 509)

1. minta: ***„Tölgyes 4” - 0-30 cm***

Össztömeg:**6100 g** ebből iszapolás után feldolgozandó/átnézendő összanyagmennyiség:**119,24 g**

Frakció bontásban: 0,5-2 mm:72,33 g



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2 mm<:46,91 g


2. minta*: „Tölgyes 4" - 30-50 cm*

Össztömege:**5150** g ebből iszapolás után feldolgozandó/átnézendő összanyagmennyiség: **86,58 g**

Frakció bontásban: 0,5-2 mm:58,88 g

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2 mm<:27,70 g

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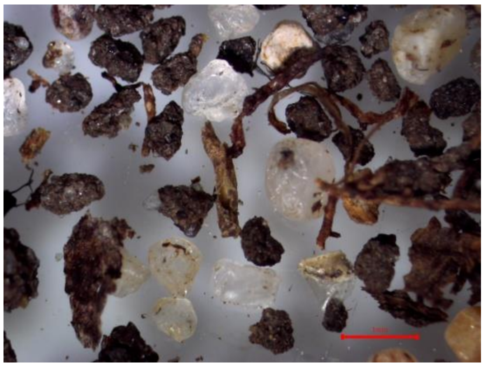
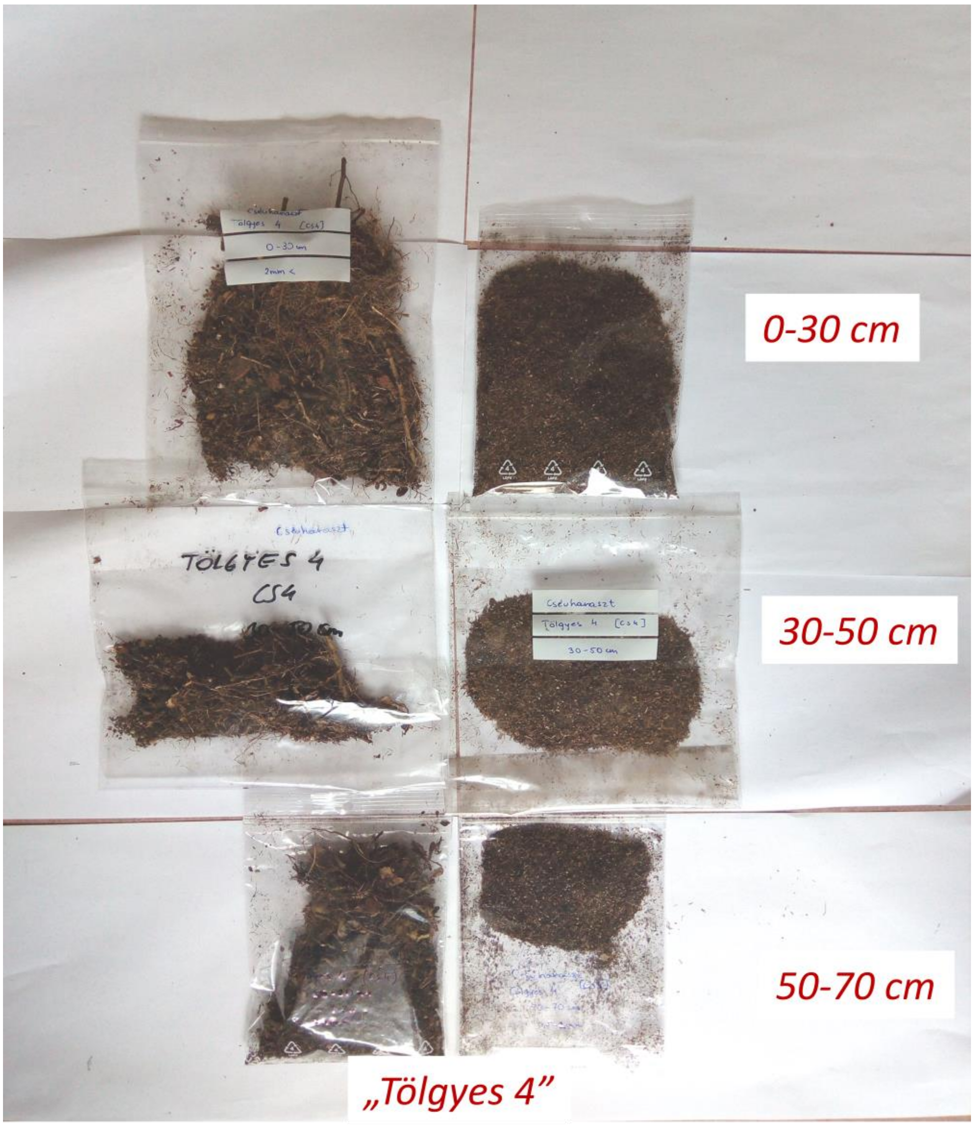
3. minta *:„Tölgyes 4" - 50-70 cm*

Össztömege:**4692,24** ebből iszapolás után feldolgozandó/átnézendő összanyagmennyiség: **77,29g**

Frakció bontásban: 0,5-2 mm:33,59 g



2 < mm:43,70g


0-30 cm
30-50 cm
50-70 cm
„Tölgyes 4”
TÖLGYES 4
CS4

Supplement 2

Bugaci részjelentés

2023.03.23.

1. Bugacmonostor – L-18 szelvény/514. sír (középkor): (Excel ábrajel:B-L-18-514)

37 db. faszén meghatározva, mind *Quercus*.

2. Bugacmonostor-CH-15, H-12 szelvény, 813. réteg;(de lehet, hogy 8/6, mert nem jól látszik) (Excel ábrajel:B-CH-15,H-12-813)

6 db. faszén meghatározva, mind *Quercus*.

3.Bugac-Felsőmonostor-N-17/1324 sír (középkor) (Excel ábrajel:BF-N-17/1324)

1 db faszén meghatározva: *Populus*

4.Bugac-Felsőmonostor-K-18 szelvény-O:278(középkor) (Excel ábrajel:BF-K-18-278)

35 db faszén meghatározva, mind *Quercus*.

5. Bugacmonostor – 40.sír (középkor) (Excel ábrajel:B-K-40)

6 db faszén meghatározva: *Populus*

19 db faszén meghatározva: *Fraxinus*

6. Bugacmonostor –K-19; 57. szint felett (középkor) (Excel ábrajel:B-K-19-57)

20 db faszén meghatározva, mind *Quercus*.

7. Bugac Felsőmonostor, Csitári tanya-95. ház; 7. ház (középkor) (Excel ábrajel:BFCS-95-7)

(1 zacskóban 1 nagy, 1 kicsi és egy közepes (benne 3 kicsi) minták, de nincsenek külön cimkézve, így nem tudom hogy az általam meghatározott „1 kicsi" az milyen objektum)

10 db faszén meghatározva, mind *Quercus*.

8. Bugacmonostor –I-10 alapozási árok (fal) felett (középkor)

Nincs benne faszén.

9. Bugacmonostor – E34 szelvény 52. sír (középkor)

Degradált határozhatatlan faszén.

Bugaci részjelentés

2023.03.29.

1. Bugac-Felsőmonostor – CLXV 88 szelvény/7. objektum (NINCS a listában, kora nem ismert) (Excel ábrajel:BF-7)

Három kisebb zacskóból összesen 30 db. faszén meghatározva, mind *Quercus*.

Egy nagyobb zacskóból összesen 20 db. faszén meghatározva, mind *Fraxinus*.

2. Bugacmonostor-G-11 szelvény 8-1 réteg (középkor) (Excel ábrajel:BF-G-11/8-1)

Összesen 30 db. faszén meghatározva, 13 db *Quercus* és 17 db *Fraxinus*.

3. Bugacmonostor-518. sír (középkor) (Excel ábrajel:BF-518)

Összesen 25 db. faszén meghatározva, mind *Quercus.*

4.Bugac-Felsőmonostor (Monostordomb)/G-11/17 objektum /gyereksír/ fa/ koporsó(Excel ábrajel: BF-G-11/17)

- Faanyag, gyantajáratos tűlevelű (NINCS a listában, kora nem ismert)

5. Bugac-Felsőmonostor (Csitári-tanya)-95.

Szenesedett magok.

6. Bugac-Felsőmonostor - I-18; D-i pillértől Ény-ra 1 m-re/járószint(középkor) (Excel ábrajel:BF-I-18)

Összesen 80 db. faszén meghatározva. Ebből *Fagus* 7 db, *Quercus* 47 db és 26 db *Populus*.

7. Bugacmonostor – (2.minta, az első az első jelentésben, abban nem volt faszén) I-10 alapozási árok (fal) felett (középkor)

Szenült magok és nagyon rossz megtartású, mérete miatt határozhatatlan faszenek.

8.Bugac-Felsőmonostor-K-18 szelvény- 279 (középkor) (két külön zacskó, külön mintánként „kezelve”)

1.zacskó: egy nagyobb és több kisebb db, 25 db-ot átnézve, mind *Populus* feltehetően egy fa darabjai. (Excel ábrajel:BF-K-18-279-1)

2. zacskó:8 db nagyobb faszén, mind *Quercus* (Excel ábrajel:BF-K-18-279-2)

9. Kalocsa Székesegyház/Északi belső sekrestye/- 411. sír (középkor) (Excel ábrajel:KSZ-411)

Főleg szenesedett bélszövet és rossz megtartású szenült faanyag, amelyek határozhatatlanok. Meghatározható 2 kis db, ami *Quercus*.

10. Szank - Kápolnahely - Belső árok É vége (középkor) (Excel ábrajel:SZKB

30 db faszén meghatározva, mind *Quercus*.

11. Kiskunfélegyháza-Templomhalom/A/6-185. sír (Árpád-kor) (Excel ábrajel:KT)

30 db faszén meghatározva, mind *Quercus*.

(1 listában van,1 nincs a listán)