Using Different Approaches of Particle Size Analysis for Estimation of Water Retention Capacity of Soils: Example of Keszthely Mountains (Hungary)

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Abstract – PSD (particle size distribution) is a key factor affecting soil hydro-physical properties (e.g. hydraulic conductivity and water retention), which makes its determination essential. Climate change increases the importance of water retention and permeability as extreme weather events can severely impair the water supply of drought-sensitive vegetation. The amount of water in soils is expected to decrease. The modified Thornthwaite model considers soil properties such as root depth, topsoil layer thickness and particle size distribution (silt and clay fraction) of soil particles combined with the most significant soil properties. At the beginning of the research, we developed a laser diffraction method to replace the standard based "pipette" sedimentation method. The theoretical background of laser diffraction measurements is already known, but their practical application for estimating soil water retention capacity is still poorly understood. The pre-sieving of soil aggregates, the pre-treatment (disaggregation and dispersion) of the samples greatly influence the obtained results. In addition to the sedimentation method, laser diffraction measurements (Malvern Mastersizer 3000) were applied with three variants of pre-treatment. For comparison, the results of a Leptosol, a Cambisol, and a Luvisol were prepared for the first modified Thornthwaite water balance model. Significant differences appeared, especially during drought periods, which could be a basis for studying soil drought sensitivity. The development of our method can estimate the water retention capacity of soil, which could support adaptive forest management plans against climatic and pedological transformations.

paricle size analysis / pipette method / laser diffraction

Kivonat – A talaj víztartó-képességének értékelése szemcseanalízissel Keszthelyi-hegységi talajokon. A Soproni Egyetem Környezet- és Földtudományi Intézetében végzett jelen kutatás fő témája a talajok szemcseméret eloszlásának a vizsgálata, melynek több célja is van. Egyik kitűzött cél a laboratóriumban jelenleg használt hagyományos és időigényes „pipettás módszer" lecserélése a gyorsabb és modernebb lézerdiffrakciós mérési módszerre. A másik cél annak vizsgálata, hogy a talajokat miként befolyásolják a klímaváltozás hatására végbemenő változások, illetve a talajok vízfelvevő- és megtartó képessége hogyan hat az erdőállományok vitalitására. A jelen cikk a kezdeti lépéseket hivatott részletesebben bemutatni három különböző talajtípuson. Egyrészt összehasonlítjuk a pipettás módszer és három különböző módon előkezelt minta lézerdiffrakciós módszerrel mért mechanikai összetétel eredményeit, másrészt bemutatjuk a mérési eredményeken alapuló vízmérleg

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modell pontosítását, mely az analitikai módszerek gyakorlati alkalmazását és erdészeti jelentőségét is szemléleti.

granulometria / pipettás módszer / lézerdiffrakció

1   INTRODUCTION

The Russian pedologist Vasily Dokuchaev was the first to define soil-forming factors. He identified the five main factors, namely geological, climatic, biological, topographical, and soil age. The massive impact of human activities is considered the sixth factor today. Soil formation processes include humus formation, leaching, and clay formation, but the most basic formation process is weathering (Blaskó 2011). Soil can be characterized as primary mineral residues mixed with secondary minerals formed by weathering and fragmentation. Mineral particle sizes in the composition vary greatly depending on the quality of the minerals and their formation or mode of fragmentation.

Different soil-forming factors and processes cause different-sized soil particles. The particle size distribution (PSD), or the qualitative characteristic expressing this (soil texture), and the relative position of the particles of different sizes are among the most important soil indicators (Stefanovits 1971). This influences many soil properties, particularly the size of the interfaces between the soil phases (specific surface area) and, consequently, the major physical and chemical processes taking place on these surfaces. In addition to the soil structure, this also affects porosity, which, in turn, affects water retention and hydraulic conductivity (Bieganowski et al. 2018). Soil porosity can be described by the total volume of soil pores and by pore size distribution. We can distinguish two main pore types: structural (inter-aggregate) and textural (intra-aggregate) pores (Beven – Germann 1982, Schlotter – Schack-Kirchner 2013). The pores can also be divided according to size, e.g. micropores, macropores, and other differentiated divisions (SSSA, 1997). Using the capillary tube model described by the Young-Laplace equation, the matric potential (water retention) can be related to effective pore diameter as follows: macropores: > 75 µm, < 1.6 pF; mesopores: 30–75 µm, 1.6–2 pF; micropores: 5–30 µm, 2–2.78 pF; ultramicropores: 0.1–5 µm, 2.78–4.47 pF and cryptopores < 0.1 µm, > 4.47 pF (Rajkai et al. 2015).

Though sedimentation methods (sieve-pipette or hydrometer method) are the most commonly used methods to determine PSD, the use of laser diffraction methods (LDMs) is also presently widespread (di Stefano et al. 2010). The pipetting method is a classical sedimentation method in which a certain amount from the suspension is pipetted after the settling time has elapsed. The dried mass of the particle fractions is then measured (*MSZ 08-0206, 1978)*. Calculations are completed according to the Stokes-law. Spherical grains are usually assigned with the density of quartz ($\rho = 2.65\ g/cm^3$). Although the particle shapes are not uniformly spherical, for calculation purposes they should be considered as such. Most silt and clay particles possess a plate or tubular structure rather than a spherical structure, so the direction of movement is perpendicular to the maximum cross-section. Thus, as the settling rate of the particle decreases, the expected *tensile strength* of the particle increases, denoting that the particle shapes affect the result (Polakowski et al. 2014).

Laser diffraction particle analysis is an efficient procedure because it takes significantly less time, covers larger size ranges, and requires a smaller amount of sample (Bieganowski et al. 2018). The definition is based on the relationship between light and surface. Light impinges on the particle surface, allowing light to refract, bend, reflect, and absorb on the surface (according to *Lambert-Beer* law). Laser diffraction particle analysis is based on the fact that the particle reflects the light beam at a certain angle, and that this angle increases as the particle size decreases. The beam of monochromatic light passes through the suspended sample, and

the beam of curved light thereby generated enters the multi-element sensor. The most commonly used PSD calculation method also assumes that the particles are spherical, i.e., the diameter of a given particle is an optical sphere (Eshel et al. 2004).

Site factors determine the occurrence and distribution of each tree species. By field factors, we mean the totality of factors that affect the growth and health of plants. Climatic factors, hydrological conditions (amount of available water from the soil), and soil properties (genetic soil types, physical diversity, and crop layer thickness) significantly influence the classification of Hungarian forest sites. Furthermore, altitude, exposure, slope, and the role of bedrock must also be considered (Babos 1966).

Site changes have accelerated in recent decades. Experts have noticed a rapid change in hydrological conditions such as groundwater level subsidence (Csáki et al. 2018). Hydrological factors change relatively quickly, but for the time being, they are mostly local problems. Climate is also a rapidly changing factor, but this change already affects the entire domestic forest population. Extreme changes in precipitation and temperature averages significantly impact the forest ecosystem and often leads to contiguous periods of drought. We can also expect climatic condition changes and soil transformation, both of which are expected to accelerate in the future due to temperature fluctuations. Two important changes in soils are directly related to climate change; an increase in soil temperature, which precipitates a decrease in soil moisture content; and altered soil moisture contents, which influences evapotranspiration and the rate of groundwater formation (Bidló – Horváth 2018).

Based on the research conducted at the University of Sopron in recent years, the spatial shift of certain climatic categories can be predicted (Führer et al. 2011, Führer 2018). In the future, the appearance of site type variants that have not occurred in Hungary must also be expected (Czimber – Gálos 2016, Mátyás et al. 2018). In order to prepare for the projected changes, the four forest climate categories used thus far had to be extended by a fifth, the so-called steppe climate category. In addition, the spatial shift of climate is accompanied by the emergence of soil types, whose formation conditions are related to other climates, plants, e.g. forest steppe. Applying planned forest management in advance of the new site type variants is crucial (Bidló – Horváth 2018).

Climate sensitive tree species and tree stand types should characterize classes of production site typology in forestry practice. Precisely measured meteorological parameters can determine climate classes (Beech, Hornbeam-oak, Sessile oak - Turkey oak, and Forest-steppe climates). Models indicate that forest climate classes will shift by the middle of the 21st century; forest-steppe climate class areas will increase, while closed forests are expected to decrease (Führer et al. 2017). The importance of individual soil properties will increase due to climate change. Concerning groundwater retention capacity, only forests with access to adequate water supplies will be able to survive longer rainfall-free periods. This ability is mainly determined by the physical soil variety and the thickness of the topsoil layer. Therefore, conducting the widest possible PSD measurements is vital to the health of our soils and forests.

The complex excavations performed in Hungary revealed that the effects of unfavourable soil properties, such as the physical variety or aggregates of coarse sand, are further aggravated by long dry and warm periods, which have been typical recently. For these reasons, the water holding capacity of our soils will become one of the most important production factors in the changing climate. The analysis of temperature and precipitation time series for a given area is suitable for detecting the effects of dry and warm periods in recent periods. The frequency of these is expected to increase in the future, especially in extreme weather situations, as well as the importance of microclimate conditions, in which exposure and forest structure will play key roles. Although weather is the primary cause of individual deforestation, soil conditions also play a very important role, as the water holding capacity of extremely shallow and shallow soils is exceedingly poor. As precipitation events have become more intense but less frequent in the

recent period, only a small portion of the precipitation that falls in this way can be stored in the soil. For this reason, we can expect that no water that can be taken up by the vegetation will remain in the soil during long dry periods between heavy rains. By predicting the expected negative effects, we can already conclude to what extent drought can aggravate the given unfavorable soil properties. Due to the long dry periods already mentioned, the declining amount of water in the soil causes so-called drought stress.

Significant deforestation occurred in the Keszthely Mountains in 2012. The devastation continued in subsequent years and appears to be ongoing even today. The destruction mainly affected the planted black pine stands, but the health of other tree species has also deteriorated. Primary studies have detected biotic pests as a damage cause, but also indicate that abiotic factors are the main causes of the destruction. Since the damage affected black pine, which has been present in the area for several decades (centuries), questions concerning abiotic factor changes arose. A chief goal of our work is to detect the changes and facilitate a solution. At the same time, questions concerning future possibilities also arise. Expected future changes may render currently reversible damage irreversible, which in turn prompts concerns about adapting to expected future site conditions as well as which tree species to use. This current paper presents the first steps of an analytical methodology development, which provides a basis for a more accurate estimation of the water retention capacity of soils. The final aim of this research is to help afforestation. More specifically, to aid climate-resistant tree species selection on a precise amount of silt and clay particle determination. The main questions of the current study are the following:

1. How can the time-consuming pipette method be efficiently replaced with a timesaving measuring instrument based LDM PSD? Furthermore, what are the advantages and disadvantages of LDM?
2. Do instrumental measurement results have better accuracy? Are those results optional for the water balance model?

2 MATERIALS AND METHODS

2.1 Durability study

Based on the previously stated objectives, we selected the Keszthely Mountains as the study area. The bedrock here is mainly dolomite. The soils of these mountains are very diverse, which makes them particularly suitable for our measurements. Due to the geological and topographical features of the area, the forests of the Keszthely Mountains have no access to surplus water, which means that the vegetation is dependent on precipitation. Most of the mountainous and hilly areas here are not under intensive land use and no upcoming land use changes are expected. Leaking wetlands in the loess areas and valleys, where oxygen-rich water moves under the cover or in the soil almost parallel to the surface, may exist to a small extent. The amount varies, but excess water is always beneficial for the local populations (Bidló et al. 2015).

In the sampling area, three soil profiles with different structures were selected to examine the organic matter content influencing the measurement in as varied a manner as possible (*Figure 1*). The topsoil layer thickness of black rendzina (BRE) is 30 cm, of which the reduced thickness is only 10 cm, which can be defined as shallow. The humus form of the soil is mull-humus. The topsoil contains organic plant residuals parts. The parent material is dolomite. Soil pH was 7.5 and was determined according to the Hungarian Standard (MSZ-08-0205/2-1978). The field capacity and the permanent wilting point of the topsoil layer was also significant. This layer hass a loam texture with a crumbly structure, containing highly humus-rich rock fragments, richly networked by roots.

Figure 1. Location of the examined soil profiles in Hungary with the elevation information and the pictures of the investigated soil types

The topsoil layer thickness of brown earth (BEARTH) is 40 cm, of which the reduced thickness is also 40 cm, which can be defined as middle deep. The humus form of the soil is mull-humus. The parent material is loess (deposited on dolomite). Soil pH was 7.6 . The texture was loam. Water conditions were favourable, water permeability was medium, and water-holding capacity was suitable. Nutrient supply was adequate. The supply of nitrogen, phosphorus, and potassium in the non-eroded section were also appropriate.

The topsoil layer thickness of lessivated brown forest soil (LBFS) is 100 cm, of which the reduced thickness is 100 cm, which can be defined as deep. The humus form of the soil is mull-humus. The parent material is loess. Soil pH was 5.8−7.9, slightly acidic in the topsoil, and the pH increased with soil depth (effect of loess). The texture was sandy loam. A typical three-layered soil. The water management of such soils was excellent, the water permeability is medium, and the water field capacity is adequate. The water storage capacity increased by the fact that the B horizon has a weak water retention effect.

2.2 Analytical methods

Standard based pipette sedimentation method (PSM)
The samples for both procedures were prepared according to a modified version of the Hungarian Standard (MSZ-08-0206, 1978). After weighing the soil sample, the organic matter was removed with hydrogen peroxide until the soil turned grey and the humus materials decomposed into water and carbon dioxide (the original standard does not suggest to destroy the organic matter). Then Na-pyrophosphate solution was added to the sample as dispersing agent and shaken for 6 hours. The soil suspension was then washed through a 0.2 mm mesh sieve into a large porcelain bowl using warm distilled water and a rubber brush. This process should be repeated until the water that drips off is transparent. The coarse sand fraction remaining on the sieve was washed into a small porcelain dish of known weight without loss

using distilled water. The suspension of silt and clay passed through a 0.2 mm sieve was washed into a 1000 ml settler, then filled with distilled water and pipetted out from the given depth after given time.

Laser diffraction method (LDM)

Since three types of treatment were conducted, a more detailed description of these follows. The previously mentioned Malvern Mastersizer 3000 particle analyser was used for the laser diffraction particle size analysis. The device itself consists of a laser light source, light processing optics, a cell, a lens, and a multi-element detector. The multi-element detector provides the diffraction pattern. A data processing unit is also needed for the deconvolution of the diffraction data, as well as for volumetric particle size distribution, related data processing, and reporting (Malvern 2013). The optical unit is the center of the system, designed to transmit red laser light and blue light through the sample. The light is transmitted to a detector, which generates data from light scattering caused by particles in the sample. The measuring cell functions as an interface between the dispersion unit and the optical unit. Wet dispersion units are designed to circulate a liquid sample through the measuring cell. Measuring range: 0.01 µm – 3500 µm. The measurement is quite simple: a Hydro EV dispersion unit is placed in a 1000 ml beaker, filled with 800 ml of distilled water, and a soil sample is added to the distilled water accompanied by ultrasound. Ultrasound prevented settling to the bottom of the beaker for heavier aggregates and prevented re-agglomeration in the samples. The blue light (λ=470 nm) was used to capture the background, while the red light (λ=632.8 nm) was used to detect particles. The rotation speed was 2750 rpm and Mie theory was applied, refraction index 1.52 and absorption index 0.1 for the dispersed phase, and refraction index of 1.33 for water as the dispersing phase.

The treatments used were as follows for instrumental measurement:

- **M1** = Sample containing organic matter: In the case of the soil samples, the organic matter content was not destroyed; only the soil was suspended and the solution was homogenized. The prepared sample was added from the shake flask to the dispersing unit.
- **M2** = $NaPO_3$ dispersed sample, pre-treated with hydrogen peroxide (H_2O_2): The second treatment is the same as the preparation for the pipette method. Adhesives in the soil include humus, iron and alumina oxides and hydroxides, and calcium carbonates ($CaCO_3$). H_2O_2 treatment is used to destroy humic substances, while diluted hydrochloric acid (HCl) should be used to remove $CaCO_3$. $NaPO_3$ was used for dispersion. Complexing agents are used to form iron and aluminium oxides (oxide hydroxides). To prevent re-coagulation of the particles, a peptizing agent (NaOH and Na brine, in rare cases Li brine) is added to the soil sample and soil suspension.
- **M3** = Sample pre-treated with hydrogen peroxide (H_2O_2) and hydrochloric acid: In the third preparation, we only destroyed the soil organic matter content. The humic substances are destroyed with hydrogen peroxide, while diluted hydrochloric acid is used to remove the calcium carbonate.

The PSD measurement results of the pipette method, considered as a standard, were compared with the LDM results obtained with different treatments using SPSS statistical software package to found find the best reliable (best correlated) LDM procedure.

2.3 Water balance model calculations

To detect drought stress, the Thornthwaite water balance model (Thornthwaite – Mather 1955) was used, which, in addition to monthly temperature and precipitation data, also includes soil

physical diversity, rooting depth, available water (EW) and maximum water uptake (EWm) (1). Monthly precipitation was reduced by an interception to determine the annual drought stress index (Is) (2). Granier et al. (1999) assumed stress when the relative recoverable moisture content (REW) of the soil drops below 40%. In the case of long-term drought period, this percentage could be higher in Hungary. Model parameters: monthly temperature and precipitation, reduced topsoil layer thickness, and root depth. Furthermore, the relative extractable water amount was refined with the data of the measured silt and clay fractions of the soils. At this point, we used the PSD results previously measured by different analytical methods. The models were prepared in MS Excel program.

$$REW = EW / EWm \qquad (1)$$
$$Is = \sum SWD / EWm \qquad (2)$$
$$SWD = EWm \cdot 0.4 - EW \qquad (3)$$

Where:

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

3   RESULTS AND DISCUSSION

3.1 Particle size distribution

All measurement results were compared during the evaluation. The focus was on the correlation between the results of pipette (PSM) and laser diffraction (LDM) particle analysis. Moreover, the connection between the three data groups measured with the instrument was considered as well. In comparing the results, the different fractions were compared separately using correlation diagrams for conclusions. *Table 1* summarizes the sums of silt% and clay%.

Table 1.   Results of the silt+clay fraction (%) determined with PSM and LDM

Soil type	Depth (cm)	S+C % (Pi)	S+C % (M1)	S+C % (M2)	S+C % (M3)
LBFS	0 – 5	25	20	12	40
LBFS	5 – 25	27	36	54	17
LBFS	25 – 60	35	40	62	33
LBFS	60 – 100	27	36	60	27
LBFS	100 – 120	11	29	48	43
BRE	0 – 15	39	13	33	56
BRE	15 – 30	17	13	32	8
BEARTH	0 – 10	49	24	69	60
BEARTH	10 – 40	43	25	31	63

S+C %: summarized value of Silt%+ Clay%; Pi: Pipette measurement; M1: Sample containing organic matter; M2: Dispersed sample treated with Hydrogen-peroxide (H₂O₂); M3: Sample treated with hydrogen-peroxide (H₂O₂) and hydrochloric acid; LBFS: lessivated brown forest soil; BRE: Black rendzina; BEARTH: Brown earth

Differently measured clay and silt fractions were compared. The clay content is interesting because it is the best efficiency indicator of the preparation methods (Kun et al. 2013, Yang et

al. 2015, Makó et al. 2017). The clay + silt fraction is one of the most fundamental input soil parameters of water balance models. For clay content, the 2 μm clay/silt fraction boundary (*Figure 2*) and the 7 μm clay/silt fraction boundary (Figure 3) were determined (Makó et al. 2019). In addition, only filtered values were entered into the program, with "obscuration" greater than 25 and "residual" results greater than 2.5 selected. Two statistical numbers were considered for the samples, the Coefficient of Determination (R^2) and the Root Mean Square Error (RMSE). The RMSE number shows both an underestimation and overestimation of the results, while R^2 value means a close or weak correlation between the pipette and the laser methods. Figures clearly indicated that the extent of RMSE varied depending on pre-treatments and fraction boundaries. The smallest underestimation or overestimation was measured for untreated suspensions by choosing the 7 μm fraction limit. The samples without pre-treatment had the highest R^2, while the lowest R^2 values were obtained for the only destroyed samples, for both limits. The highest RMSE value was observed for the destroyed and dispersed samples at the 7 μm clay boundary. Considering all the pre-treatments, it can be said that the R^2 values were slightly higher for the 7 μm fraction limit, while for the 2 μm fraction limit we found a smaller underestimation or overestimation on average.
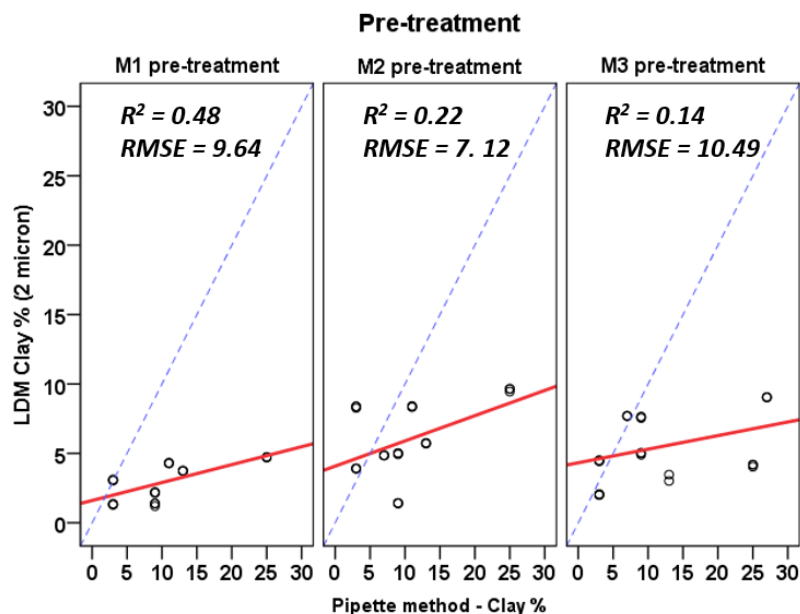

Figure 2. Comparison of clay content at 2 μm fraction limit determined with pipette and laser diffraction method

The 2 and 7 micron limits do not require separate evaluation for this fraction, as their sums are the same. On Figure 4. values marked in brown represent samples with high organic matter content from the upper horizons. The values show a low regression at first glance and a rather large overestimation. The only acceptable value ($R^2 = 0.41$) is shown for M3 due to the high soil organic matter (SOM) content of each sample. However, the confounding effect of SOM did not appear in this sample because if we take out the data marked in brown, we still obtain a good regression fit. In the case of the M1 sample, the data with a high organic matter content stand out from the other values. There are two possible reasons for this. It is possible that some of the clay + silt content remained in the form of aggregates and that the incorporation of ultrasound did not help to separate the aggregates. Another possibility is that the undestroyed organic debris, which remained in the suspension, hindered the laser measurement. The coexistence of these two options interfered with the poor regression relationship ($R^2 = 0.08$). If

the data marked in brown are taken out of the analysis, a high regression line is obtained (R^2 = 0.94).
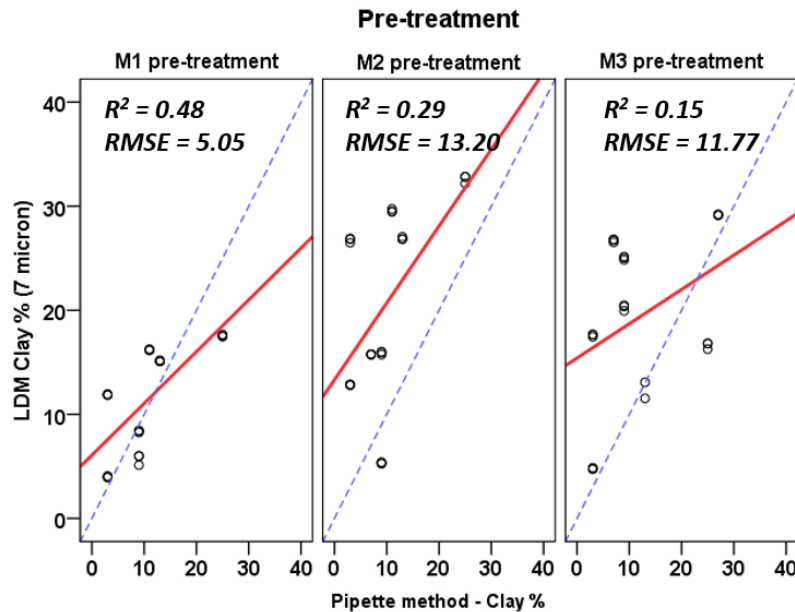

Figure 3. Comparison of clay content at 7 μm fraction limit determined with pipette and laser diffraction method
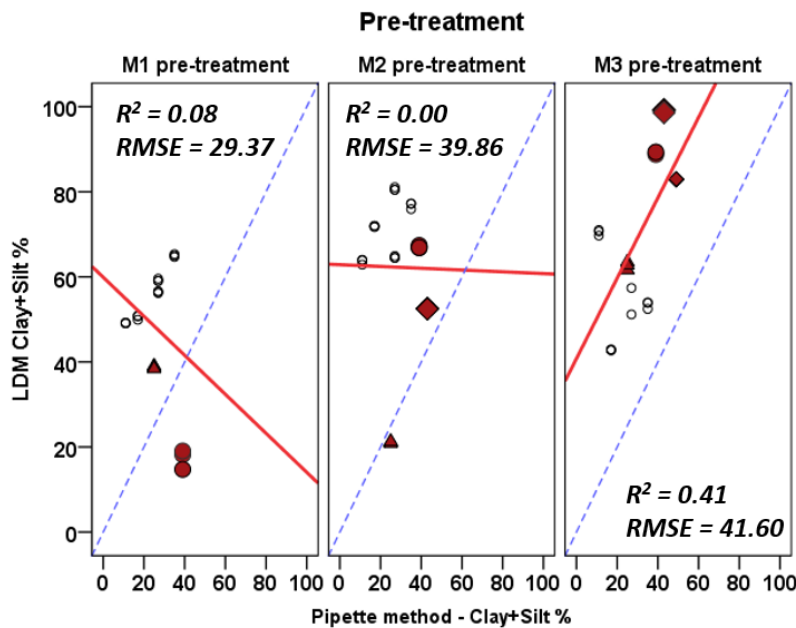

Figure 4. Comparison of three type of instrumental measurement

The destroyed and dispersed (M2) sample displays the same behaviour (*Figure 4*). The value of R^2 (= 0.00) is weak as well, but if we take these high organic matter contents out of the evaluation, we get a better fit (R^2 = 0.42). To conclude, the clay + silt content always overestimates the pipette clay + silt content in laser diffraction measurements. In the cases of M1 and M2, this occurred even without the samples with high SOM content, and in the case of M3, it even occurred in the samples with high SOM content. Promisingly, Igaz and colleagues (2020) performed PSM and LDM comparisons on 542 soil samples and found that a

polynomial-based regression model is adequate for obtaining an approximation of the pipette method and laser tools (Malvern Mastersizer 2000, Fritsch Analysette22) after recalculation of the data.

For practical applicability, the obtained results were used to construct the Thornthwaite monthly water balance model. To prepare the water scales, we first used the pipette measurements followed by the values obtained with the laser instrument. Following the measurements, water scales for the three studied soil types were prepared to investigate the relationships between the soil particle properties and the water retention capacity. Water balance diagrams were prepared using the properties of the soils and the climatic conditions of the area (Gálos et al. 2017, Bidló et al. 2019). It is important to note that below a certain limit, plants cannot absorb enough water and water stress develops.
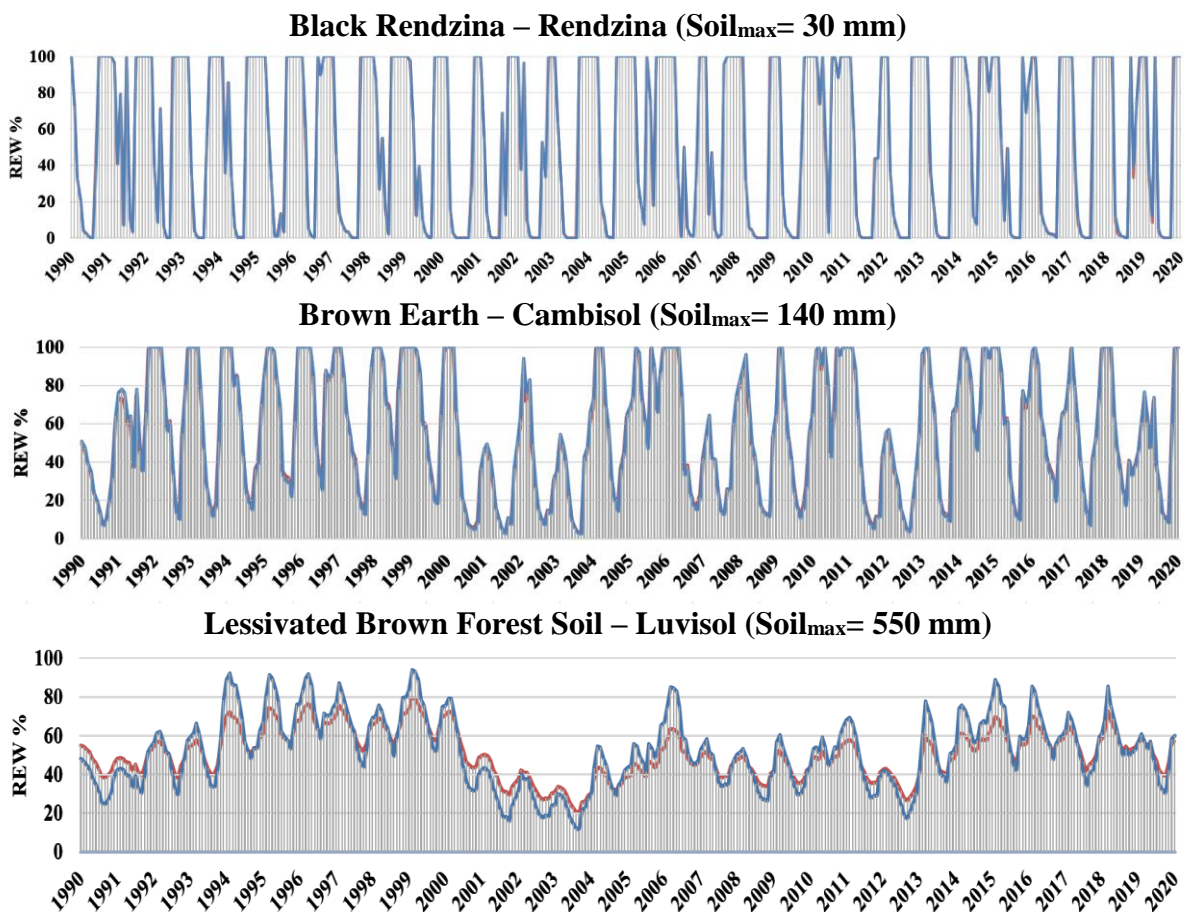

Black Rendzina – Rendzina (Soil$_{max}$= 30 mm)

Brown Earth – Cambisol (Soil$_{max}$= 140 mm)

Lessivated Brown Forest Soil – Luvisol (Soil$_{max}$= 550 mm)

Figure 5. Water balance models derived from results of pipette (red line) and M2 laser diffraction measurements (blue line) (Soil$_{max}$: maximum amount of water that can be stored for an emptied soil during a precipitation event, REW%: relative extractable water amount)

Figure 5 displays the comparison of the Pipette method (blue colour) and M2 (red colour) measurements made by the similar pre-treatment.

In the case of LBFS, the water was well retained and evaporated slowly during the drought periods, of which there were three (1990-1993; 2000-2003; 2011-2013). These conditions ensured continuous forest cover. Mention should also be made of the amount of water stored in the soil, which is 500 mm, and the thickness of the reduced topsoil is 100 cm.

BEARTH absorbs water relatively quickly, but it releases it just as quickly due to the physical variety of the soil. The maximum amount of water that can be stored in the soil is 100 mm, which is already significantly less than LBFS. During drought periods, this soil type was

already much less able to store enough water for vegetation. The figure also clearly shows the difference in years with very high rainfall (e.g. 2010), when plants were relieved from water stress.

For the BRE soil type, Figure 5 illustrates that the soil saturates quickly, but also loses water content quickly, especially during drought periods. The maximum amount of water that can be stored is small (30 mm) due to the shallow (15 cm) thickness of the crop layer, which, however, has an exceptionally high organic matter content. The water retention capacity of the soil is no longer enough to maintain closed forests.

The three different figures clearly show that LBFS with a deep topsoil layer thickness is much more sensitive to water loss during drought periods. The measurement differences are mainly visible in the LBFS water balance, especially in drought years when the instrument over-measures. After 2-3 years of drought, the Mastersizer measurements underestimate, and then the difference in measurements decreases in the following years. Therefore, analytical studies require further investigation to draw further conclusions.

4   CONCLUSIONS

Determining the particle size distribution of soils helps to monitor the hydro-physical properties of the soil (e.g. hydraulic conductivity or water retention). Climate change increases the importance of water retention and permeability as extreme weather events can severely impair the water supply of drought-sensitive vegetation. Overall, the amount of water is expected to decrease in the future.

As a first step of this research, we developed the laser diffraction method, which is a faster and more reliable pre-treatment measurement method than the classical "pipette" sedimentation method. The theoretical background of laser diffraction measurements is well known, but their practical application for estimating soil water retention is still poorly understood. (Yudina et al. 2020). The modified Thornthwaite model considers soil properties (e.g. root depth, topsoil layer thickness) and particle size distribution (silt and clay fraction). In addition to the sedimentation method, laser diffraction measurements (Malvern Mastersizer 3000) were conducted with three variants of pre-treatment.

- The pre-sieving and pre-treatment of the samples greatly influence the obtained results. Weak regression lines and high underestimations are possible due to sources of error from pre-treatments.
  Explanation: During organic matter decomposition, it is likely that not only the humus content decomposed. The undegraded organic debris from the topsoil in the samples may have remained in large quantities. The aggregates and the mineral phase may also have been destroyed by removing organic materials and carbonates, which may have resulted in the decomposition and transformation of some of the clay minerals.
- For laser diffraction measurements, sampling from the suspension can also be a source of error, as a significant part of the sand fraction presumably settles down, which means the suspension could not be dispersed evenly.
  Explanation: This can be seen in the determination of the clay + silt content when overestimating the samples. Another possible source of error is that the soil suspension could not be completely washed out. After decomposition, dissolved, possibly semi-decomposed, organic substances such as hydrogen peroxide may have formed, which may have formed a precipitate with the dispersant during sonication. Therefore, the correlation between pipette and laser diffraction measurements may be weak.
- Based on our results, the particle size distribution has great importance in determining the water retention capacity of soils. We obtained lower-than-expected correlation

values for the particle size distribution determined in different ways, which could be due to several reasons (Yang et al. 2015, Bieganowski et al. 2018).

Explanation: One such reason is that the laser diffraction instrument gives a volume percentage, while pipetting measurements give weight percentages. The density of soil particles greatly influences pipette measurements. This parameter is negligible with laser diffraction measurement. However, in the latter case, the refractive index of the particles can be a significant factor.

The current study indicates that laser diffraction measurement can replace the classical sedimentation (pipette) method in the near future. These facts are sufficient to obtain different results. In addition, the removal of organic matter also worsened the correlation of the results. For comparison, the results of a Leptosol, a Cambisol, and a Luvisol were prepared for the first modified Thornthwaite water balance model. Significant differences appeared, especially during drought periods, which could provide a basis for studying the drought sensitivity of soils. The development of our method allows for the estimation of the water retention capacity of soil, which could help forest management in planning adaptations to climatic and pedological changes.

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