Final report of the project OTKA PD 115833 "Developing LIDAR technology for quantitative mapping of wetland biodiversity and ecosystem services"

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This project was an interdisciplinary study bridging ecology and remote sensing algorithm development with the aim of establishing field-calibrated LIDAR algorithms as the new standard in wetland vegetation biodiversity and ecosystem service assessments. This involves two paradigm shifts: the state of the art in ecosystem service assessment was that service proxies can merely be estimated using generic assumptions and that quantifying them using physical quantities measured in situ is too challenging. The state of the art in using LIDAR for vegetation structure and heterogeneity mapping is that forest ecosystems can readily be studied with airborne laser scanning, but herbaceous vegetation has too fine structure to be quantified with this method. The results of the project significantly advance the state of the art by disproving these assumptions: we demonstrate that field indicators for multiple biodiversity and ecosystem service parameters can be efficiently collected, even with very limited resources, and these parameters relate strongly to established properties known to relate to ecosystem services. We also demonstrate that vegetation mapping from LIDAR can include vegetation classification, structure and heterogeneity measurement and ecosystem service proxies with significant accuracy and plausible models.

In the following, we present the results of the project according to the structure of the key questions, hypotheses and targets laid out in the submitted Research Plan.

Main hypothesis: *LIDAR and field-based biodiversity and ecosystem services mapping provide better quantification than the state of the art method of benefit transfer upscaling with land cover data.*

Currently available datasets for comparison include the Copernicus Wetland layers and the NÖSZTÉP Hungarian National Ecosystem Service Assessment Wetland map. Neither of these was found to be a suitable basis for comparison: the Copernicus Wetland layer is defined according to the wetness of the soil and not the vegetation itself, while the NÖSZTÉP dataset only focuses on wetland naturalness and does not aim to provide quantities comparable with our measurements. However, our hypothesis that LIDAR provides successful mapping of these variables in a multi-parameters setup is proven, as detailed below: the field protocol enabled wide-area quantification of nearly all target variables (except decomposition and human presence), the LIDAR datasets enabled high accuracy classification of mean vegetation types, and models for predicting biodiversity and ecosystem service proxies have been successfully established.

What field measurements, what sampling effort and layout provide the best reference dataset for biodiversity and ecosystem services quantification by LIDAR?

The combination of two sampling levels, ie. direct measurements and quick measurements proved to substantially reduce sampling effort while not compromising calibration accuracy. For the parameters vegetation height (R^2 0.51), underwater number of stalks (0.71) total biomass (0.68), leaf area index (0.41), foliage height diversity (0.62), and vegetation height distribution (0.91), significant correlations were obtained between the quick and direct samples, which supports the use of the quick indicators for LIDAR calibration. However, it is essential that the two sampling types are carried out within the same transects.

The limitations of the proposed measurement strategy are the decomposition experiments, which produced too heterogeneous results for quantitative evaluation, and the air humidity and temperature sensors, which proved not to tolerate the wetland conditions.

Which LIDAR data products and suitable as indicators of biodiversity and ecosystem service potential?

For biodiversity, the class probabilities obtained from fuzzy vegetation classification are the strongest predictors, since these correlate strongly with the vegetation class and allow assessment of beta diversity (vegetation class diversity) in simple kernel filtering approaches. Vegetation classification Cohen's Kappa values are between 0.84 and 0.87 for four dominant vegetation classes. For vegetation structural diversity, horizontal spatial heterogeneity of leaf area index can be assessed based on the number of LIDAR echoes, and foilage height diversity is anticipated to strongly correlate with Rao's Quadratic Entropy of point heights based on initial tests. Microclimate-related services show strong correlation with distance to

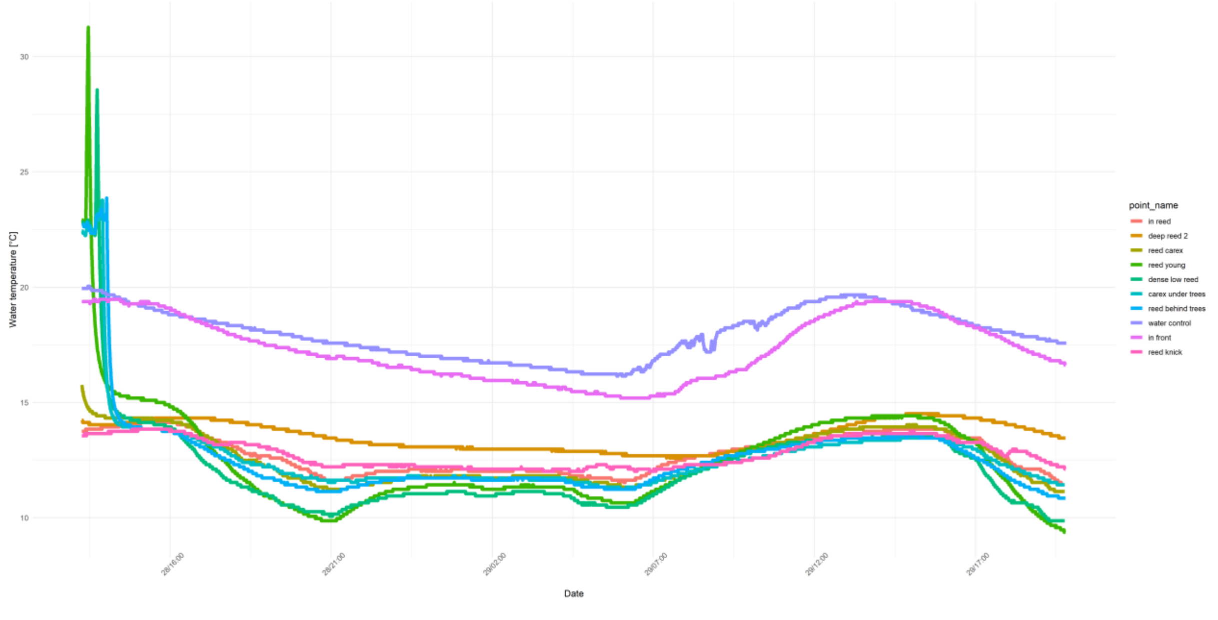

Figure 1: water temperature graph at the Szigliget study site, showing the cooling effect of wetland vegetation compared to the control (magenta)

wetland edge, with water temperature dropping steeply where the influence of open water in the wetland ends (Fig. 1). Leaf surface, and gap fraction (shading) as already mentioned, correlates favourably with various LIDAR indices (albeit different indicators for the different study area datasets). A novel algorithm for biomass estimation has been developed, showing correlations up to 0.8 with biomass indicators during initial tests.

How reliable is the system, what are the costs and benefits?

The reliability of the system depends strongly on the LIDAR survey parameters. The point density has a stronger influence on correlations with LIDAR parameters than the flight season: the Lake Tisza datasets with >10 pt/m^2 (collected specifically for vegetation mapping) provide visibly better representations of spatial patterns than the other sensor datasets. The return on investment is the most favourable for regions where pre-existing LIDAR data are available, such as the Austrian state of Burgenland. The main cost is the workload associated with fieldwork and the pre-processing of field data, while the demand for computing power is also rather high and may surpass the abilities of research institutions not focused on remote sensing.

Sub-projects: LIDAR methodology development and calibration

Hypothesis: *LIDAR data can be used to map vegetation extent, structure, map different plant associations and terrain topography in an automatic processing algorithm. These variables can be evaluated together to deliver representations of wetland BD and ES with high accuracy, very high resolution (< 10 meters) and wide area coverage (entire lake/river/estuary systems), at prices comparable to or better than only fieldwork.*

This hypothesis was successfully proven: LIDAR data allowed classification of wetland habitats into vegetation extent maps, delivered maps of vegetation structure and terrain topography using algorithms ready for massive-scale processing. Accuracies compare favourably to the accuracies of comparable remote sensing methods (eg. airborne SAR for biodiversity mapping), map outputs are generated with 2.5 m and 10 m resolution, study areas cover entire lake systems based on LIDAR coverage, resulting in hundreds of thousands of pixels. The cost of obtaining comparable accuracy from fieldwork alone (eg. sampling 1% of the pixel locations) would require about 200 times the fieldwork effort invested in this project, and would therefore be prohibitively expensive.

Which LIDAR-derived parameters, which processing algorithms deliver the best results for vegetation and terrain mapping?

For the purpose of terrain maps, the existing terrain classification within the delivered point clouds was tested and contrary to the expectations, the normalized vegetation heights obtained from the process were found sufficiently accurate. For vegetation mapping, calibrated reflectance proved to be essential, in addition to the quantiles of the point height distribution and the pseudowaveform index. For vegetation mapping, entropy of point height distributions was one of the newly discovered indicators (Fig. 2), but already established indicators such as vegetation height and point count in height layers also showed adequate correlations to vegetation indicators during initial tests.

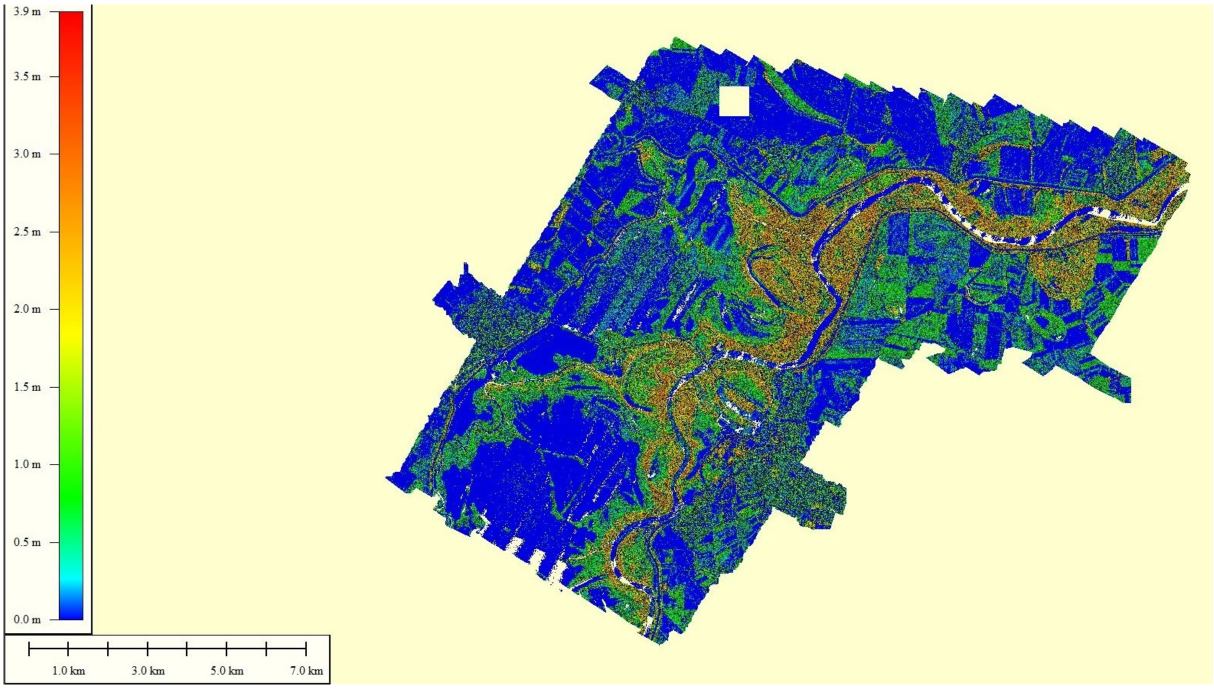

Figure 2: point height entropy (Foliage Height Diversity) map of the Lake Tisza study site

What are the minimum and optimum requirements for sensor settings and survey planning?

Some of the datasets applied during this study are close to the minimum requirements. Both leaf-off and leaf-on data can successfully be used, but point densities above 10 pt/m2 are essential. Full waveform recording significantly improves classification performance. The time lag between LIDAR flights and fieldwork is probably an important factor of uncertainty, but in our case the observed differences of 2-6 years were still acceptable.

How closely can LIDAR-derived variables correlate with indicators of BD and ESP, what other parameters have to be taken into account?

The correlation between LIDAR-derived variables and biodiversity or ecosystem service indicators depends strongly on the complexity of the model applied. Multi-parameter machine learning or generalized linear models from a high number of data rasters can produce stronger correlations, but these will be less useful for gaining information on the ecological reasons behind the patterns. Single-parameter models produce correlations between 0.1 and 0.8, which depends strongly on the lake. Typically, locally trained models will perform significantly better than benefit transfer models integrating information from all three studied lake systems.

What are the minimum and optimum mapping units?

The mapping units depend strongly on the resolution of the LIDAR data, but also on the size of the field samples. Most LIDAR texture indicators are calculated in neighbourhoods of at least 4-8 points, but 10-20 points per raster cell seem to be an optimum. In our case, this means that 2.5 meter raster cells are sufficiently large for most datasets (Fig.3) .

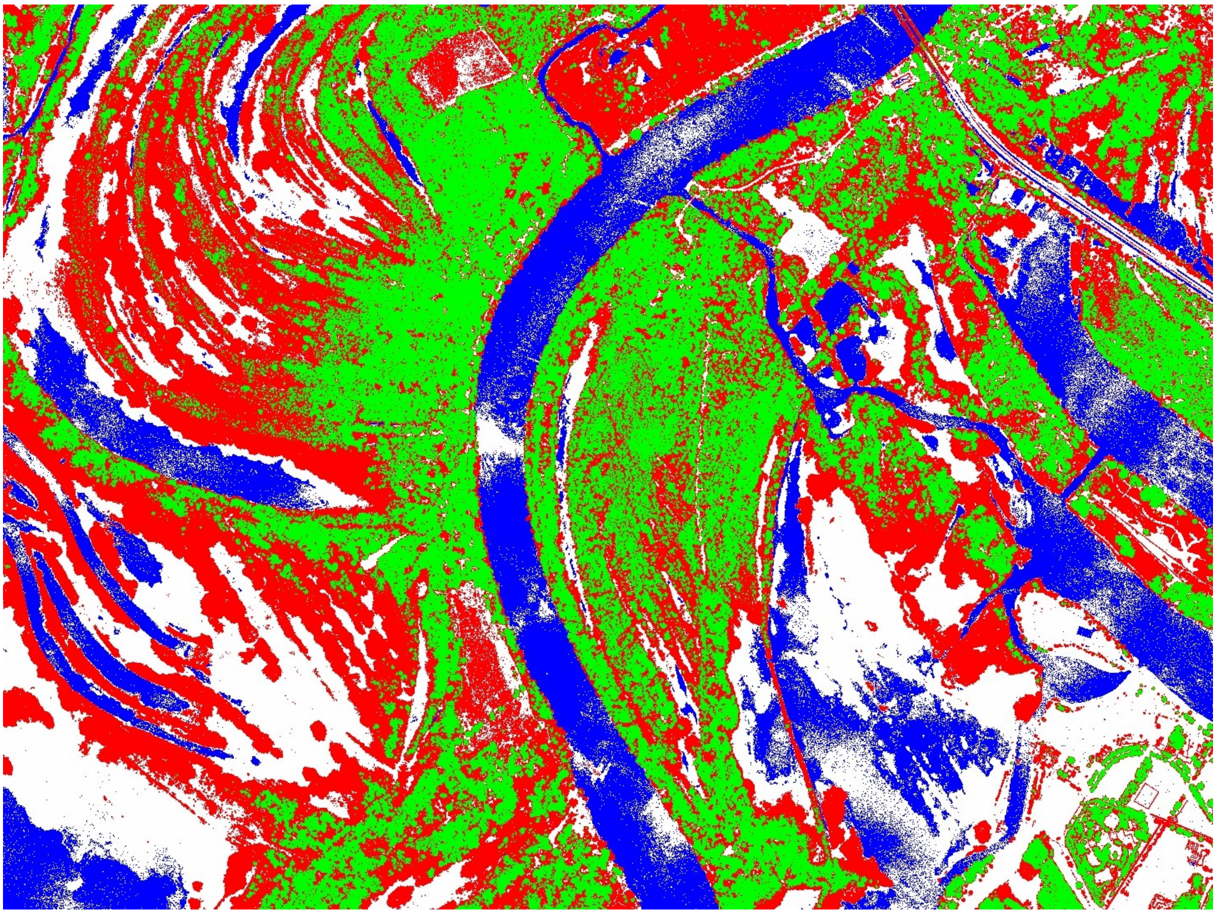

Figure 3: cutout of the LIDAR-based vegetation classification of Lake Tisza. Blue: open water, Red: reed, White: Typha, Green: Trees

Sub-project: Fieldwork

Hypothesis: *In a suitable setup, low-cost instruments together with satellite positioning and field surveys can deliver data on wetland BD and ES, with accuracy and reliability sufficient for scientific studies and also decision support. Comparing wetland measurements with simultaneous non-wetland control recordings gives sufficient direct representation on wetland ES.*

The instrumentation and fieldwork carried out here is shown to successfully deliver information on wetland biodiversity and ecosystem services. Particularly the indicators where the quick and direct measurements could be carried out with similar methodology showed strong correlations. The proposed protocol even allowed verification of the accuracy of the harvesting-based biomass measurements through the comparison of the total biomass values with the sum of the measured biomass for each height interval. Error propagation can be rigorously followed from field data to remote sensing proxy. However, not all indicators were successfully established. Human use of wetlands proved to be impractical to measure both in the field and from LIDAR data: wetland paths and tracks could not be well identified in the field and automatic identification from LIDAR data could not be developed either. The anticipated adaptation of forest road mapping LIDAR methodologies to wetlands was not successful. Also, the decomposition experiments showed that biomass sample weight loss is influenced by too many factors besides wetland vegetation tpye and status. Water regime and sediment transport were observed to be key factors in the decomposition of deployed biomass samples, and these can not be readily measured with LIDAR. The application of non-wetland controls for microclimate was successful and feasible, and the transect setup supported quantification of the effect of the wetland vegetation.

How many measurements are needed for a reasonable representation of wetland biodiversity and ecosystem services?

Our results are on par with the literature as they show that at least 50 measurements are needed for adequate calibration and evaluation. In our case, this meant that for parameters where the quick indicators could well be used, specific algorithms could be developed for the individual lakes, while for those where the fit between the quick and the direct indicators was insufficient (eg. dry biomass ratio), only a general model for all three study sites could be used. This limitation also meant that models restricted to reed vegetation (excluding samples dominated by other dominant plants) generally performed better, and sampling of other vegetation classes (*Carex, Typha*) often inadequate to develop specific calibration algorithms.

What kind of sensors and measurements allow an efficient representation of these variables, transferable to other study sites in a non-commercial setting?

The most important discovery of the field setup is that foliage height diversity can be effectively quantified in wetlands. Foliage height diversity (FHD) is recognized as one of the most important parameters of vegetation structure influencing biodiversity already since the 1960-s. However, methods for rapidly and reliably quantifying FHD were only defined so far for forests and even there, their accuracy was questionable. Here we successfully validate the pole contact method for quantifying density of individual vegetation layers against harvesting-based highly accurate references. We found that the classically used Shannon entropy based

FHD metric provided a lower correlation between the pole contact measurements and the harvested biomass (0.237) than the recently proposed Rao's quadratic entropy index (0.407).

Leaf Area Index is closely connected to structure-related ecosystem services. The photography-based method we used here (Fig.4) was adapted from a similar method used in agriculture, and the free Green Crop Tracker software proved to be an efficient solution. The correlation with total leaf weight in harvested samples was stronger than the correlation with total weight (0.32 vs 0.15), suggesting that this method truly quantifies leaf area. The use of a light fieldproof camera as opposed to a high-end camera or a smartphone proved to be a good choice as this instrument was very reliable and could also be used for documentation of the measurement process with good quality photos.

Figure 4: example of a zenith-facing photo used for quantification of leaf area index

The Hobo Pendant water temperature sensors were reasonably priced and sturdy enough for the wetland conditions: one of them was lost during the first year, but located again after two years, and found to be fully functioning. Accurate absolute calibration of these sensors was not required as a non-wetland control was always used. However, the air temperature and humidity sensors encountered several problems. First of all, temperature measurements were sometimes compromised when the instruments came into direct sunlight, resulting in erroneously high readings. Additionally, battery failures were common and by the end of the project, nearly all sensors ceased to function, most probably due to water ingress.

At the beginning of the project, it was decided that biomass shall be measured in the field, without the customary process of oven-drying samples to obtain dry weight which is easier to convert to carbon stocks. In our case, we aimed to put together a protocol that allows efficient movement even under adverse wetland conditions, and this would have been made impossible if it were necessary to remove >10 kg of wetland biomass and dry the samples in a laboratory. Even the conversion from leaf weight to leaf area using photographic methods proved to be unfeasible, since the leaves of wetland vegetation shrink and roll within minutes after harvesting. The advantage of this trade-off was that a relatively large number of harvesting samples could be collected in a short time, especially when student field assistants were available (Fig. 5).

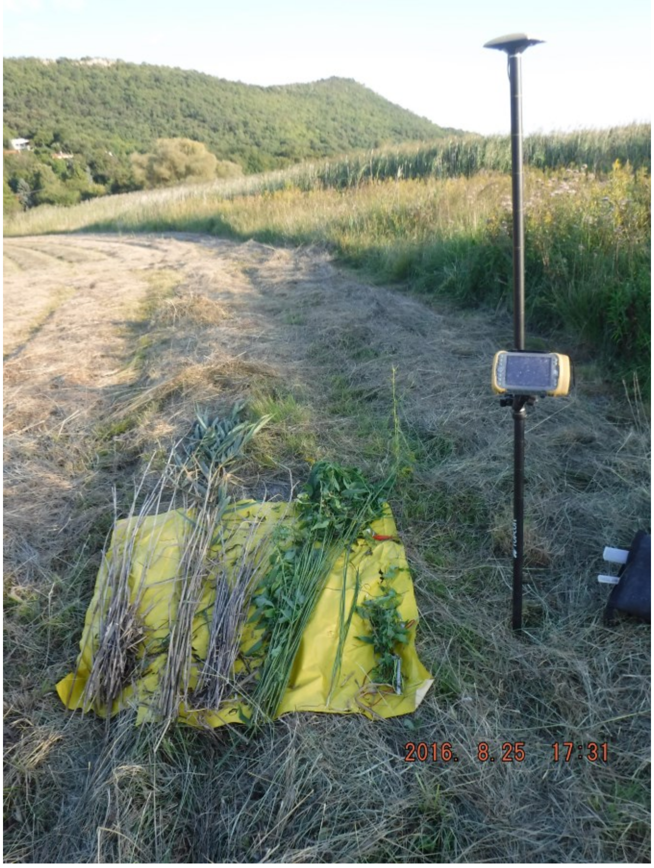

Figure 5: example of a harvested field sample, grouped by vegetation genus

Which parameters can be measured with such an infrastructure with the best accuracy?

The quantification of the wetland's effect on microclimate could be measured with relatively high accuracy and with large sample sizes, since this was only limited by the number of sensors that could be deployed during point sampling. However, in some cases the representativity of the microclimate measurements for the general effect of the wetland could be questioned. Ideally, microclimate effects should have been tested under both warm and cold weather conditions. Biomass was another parameter where verification proved that the harvesting-based field measurements were highly accurate. Biomass measurements in height layers were successfully used for quantification of foliage height diversity.

Sub-projects: Synthesis

Hypothesis: *Lidar allows efficient comparative studies with high spatial resolution, allowing direct upscaling by area and quantification of the role of wetlands in the landscape. In presence of adequate field reference measurements, LIDAR can be calibrated to a set of variables closely resembling various BD and ESP indicators. The proposed methodology is more accurate and more detailed than the state-of-the-art in benefit transfer.*

LIDAR datasets calibrated using standardized field measurements truly allowed comparison of three major lake systems in Hungary. Lake Fertő has a large reed belt characterized by conditions that markedly differ from the open water of the lake, as shown by the strong gradient in water temperature measurements. However, horizontal heterogeneity is limited since most of the wetland belt is dominated by reed. High leaf area index values are partly caused by dense standing dry vegetation from previous years. Lake Balaton has both land and water reed, with different ecosystem services. Land reed has higher species richness and is taller and more dense, while reed standing in water delivers underwater surface essential for spawning of aquatic animals. Microclimate mediation is weaker than on Fertő since in most places the width of the reed belt is less. On Lake Tisza, the spatial heterogeneity of the wetland zone is very high, with microtopographically induced zonation causing complex patterns. In some locations, extremely tall but sparse reed stands occur with high biomass but relatively low leaf area. Wetland vegetation provides shaded and humid conditions that are essential for insects and amphibians.

How does the accuracy of LIDAR-based methods vary between different wetland types and settings?

The heterogeneity of wetland types strongly influences the accuracy of the LIDAR maps, but evaluating this is problematic since the sensor settings and the time lag between the flights and the fieldwork also differed between study sites. Theoretically, high resolution full waveform data captured on Lake Tisza should have provided the best results, but extrapolation was not straightforward due to the large coverage of Typha, which was sampled less throughout the project than reed.

What adjustments should be made to the processing and the ground truthing method?

The spatial layout of the field samples would have merited more consideration, ideally with stratified random sampling or active learning. Instead of the 100 g biomass samples used here for the decomposition experiment, tea bags buried in the sediment would have been easier to handle and therefore would have enabled sufficient sample sizes for quantification of this ecosystem service as well, as a recent worldwide experiment has shown. Accurate measurement of vegetation height should be part of the point measurement protocol as well, as this is one of the most important factors influencing wetland ecosystem services. Finally, more robust air temperature and humidity sensors would have allowed collection of substantially more data on this aspect of microclimate.

What is the optimal amount, layout and timing of field measurements? How does the resolution and accuracy compare to benefit transfer-based methods?

For a single lake system, 50 direct and 200 quick measurements should provide sufficiently strong calibration. Ideal layout would have to be based on stratification by vegetation type, while timing should correspond to vegetation climax in August or September. Spatial resolution of the produced maps is at least twice as detailed as the comparable data layers that can be obtained from eg. Sentinel-2 satellite imagery.

During the lifetime of the project, the results and findings have already been incorporated into multiple *additional studies*, significantly broadening the uptake of the results. In collaboration with MTA SZTAKI, the field-based and LIDAR-based wetland maps have been used as ground truthing for satellite-based wetland mapping and monitoring, thereby expanding the results from LIDAR to satellite imagery. In collaboration with TU Vienna, some small experiments have been carried out using terrestrial laser scanning for quantifying vegetation movement in relation to water transport. Although not directly related to the focus of this project, these experiments did not receive any additional funding beyond the working hours paid from this project, and generated worldwide media interest, including listing by New Scientist as one of the "biggest and best science stories of 2016". This media interest resulted in widely increased attention of vegetation ecologists towards LIDAR, effectively multiplying the uptake of the results of this project. Finally, collaboration with the Ecoinformatics and Biodiversity Section of Aarhus University has been established, resulting in the nationwide application of LIDAR for biodiversity modelling in Denmark. This project proved that the approach and methods developed in this project are not only applicable to wetlands: LIDAR has potential for predicting species richness across all habitats, at extremely large spatial extents.

Additionally, during the lifetime of the project, significant *scientific outreach* activities have been carried out. These started with the promotion of LIDAR for mapping non-forest vegetation conservation status in Hungarian printed and online news but also in international media such as New Scientist. Dissemination was continued focusing on the topic of vegetation movement assessment by LIDAR, resulting in a series of scientific outreach publications both in Hungary and abroad. Additionally, online news articles, radio interviews and television features related to the limnology of Lake Balaton and the status and ecosystem services of wetlands were broadcasted during the latest years of the project. Based on the results of this project, the #szabadonbalaton science-art initiative was launched and has reached thousands of stakeholders, mainly around Lake Balaton. Finally, during the last project year, a public outreach video was recorded and broadcasted by the leading Hungarian online news outlet, which has received more than 65000 views.

Scientific recognition received during the project include two international poster awards (EGU 2016 and ISPRS 2016) and one national-level scientific award (Junior Environmental Scientist Award of the Hungarian Academy of Sciences), the feature by New Scientist in the "12 biggest and best science stories of 2016" (for the tree movement study) and last but not least, a cover image of Nature Ecology and Evolution.

Involvement of students

During the course of the project, two MSc students were supervised, each delivering their own results that linked to the project topic. Eszter Szabó (BME) studied the effect of reed wetlands on mitigating seiche-induced floods on the southern shore, while Tamás Gyenese compared wetland temporal dynamics to sediment processes. Student assistants were also involved in the project work, with one of them (Zsófia Koma) advancing to a PhD programme of Amsterdam University on LIDAR for Ecology. I have delivered three "Airborne LIDAR for Ecology" PhD courses at Aarhus University, two Airborne LIDAR Analysis master courses at Eötvös University and one short course on LIDAR for Tree Physiology at the University of Western Hungary.

Career Advancement

This project has allowed me to advance my scientific career not only in academic research, but also in decision support. Based on these results, I have received a scholarship to Aarhus University, to one of the leading study groups in macroecology. Additionally, I have been contracted by the Hungarian Water Authority to contribute to long-term planning of Lake Balaton with the aim of sustaining ecosystem services on the long term. The results of this project have been the basis of an ERC Starting Grant application (which reached evaluation level B)

Future studies and analysis

The data processing for this project will continue further: statistical tests of LIDAR indicators are still being carried out, and these will be the basis for calculation of final calibrated maps for the full study area, in collaboration with the University of Debrecen and Amsterdam University. Vegetation mapping is finalized and the relevant publication is close to submission. Additionally, a publication establishing the use of fuzzy mapping for vegetation analysis is also close to submission.