Final report of research project K- 105167 entitled

"*Analyses and integration of spatial and thematic properties of soil maps and databases for the compilation of countrywide, digital soil maps*"

Summary

At its beginning, our research project was entitled by an appropriate acronym: DOSoReMI.hu. Phrasing: Digital, Optimized, Soil Related Maps and Information in Hungary. These terms express the main objectives of our work that is to broaden the possibilities, how demands on spatial soil related information could be satisfied in Hungary, how the gaps between the available and the expected could be filled with optimized digital soil (related) maps. During our activities we have significantly extended the potential, how goal-oriented, map-based soil information could be created to fulfill the requirements. Primary and specific soil property, soil type and certain tentative functional soil maps were compiled. The set of the applied digital soil mapping techniques has been gradually broadened incorporating and eventually integrating geostatistical, machine learning and GIS tools. Soil property maps have been compiled partly according to GlobalSoilMap.net specifications, partly by slightly or more strictly changing some of their predefined parameters (depth intervals, pixel size, property etc.) according to the specific demands on the final products. The web publishing of the results was also elaborated creating a specific WMS environment.

Introduction

Hungary has long traditions in soil survey and mapping. Large amount of soil information is available in various dimensions and generally presented in maps, serving different purposes as to spatial and/or thematic aspects (Várallyay, 2012). Increasing proportion of soil related data has been digitally processed and organized into various spatial soil information systems (Pásztor et al., 2013). The existing maps, data and systems served the society for many years, however the available data are no longer fully satisfactory for the recent needs. There were numerous initiatives for the digital processing, completion, improvement and integration of the existing soil datasets. Until recently soil data requirements were fulfilled with the available datasets either by their direct usage or after certain specific and generally fortuitous, thematic and/or spatial inference (Dobos et al., 2010; Sisák & Benő, 2014; Szabó et al., 2007; ***Laborczi et al., 2013***; ***Szatmári et al. 2013***; Waltner et al., 2014). Due to the frequent discrepancies between the available and the expected data, notable imperfection may occur in the accuracy and reliability of the delivered products. The DOSoReMI.hu project was started intentionally for the renewal of the national soil spatial infrastructure in Hungary (***Pásztor et al. 2014b,d; 2015***).

During the mapping activities carried out in the frame of DOSoReMI.hu we relied on the rich legacy and sparse recent soil observations, which were processed, have been organized digitally by various institutions in the last decades. Simultaneously, an extended environmental variable library was set up consisting of spatial data themes related to soil forming factors as well as indicative environmental elements. A data analysis and mining module (set of quantitative procedures) was also created. At last but not least, spatial soil data demand evaluation was carried out to organize and rank the mapping activities along more objective goals.

Environmental variable library

For the mapping of soil properties, relevant auxiliary environmental variables were used. The variables were selected to characterize the soil forming factors, which determine the predicted soil properties. Furthermore, multitemporal and multispectral remotely sensed images were used, which provide direct information on the surface and certain indirect information on subsurface conditions ruled by soil features. The ancillary data set is presented in Table1.

For the characterization of terrain, we used the relevant part of EU-DEM. Numerous morphometric derivatives were calculated using SAGA GIS software (Conrad et al., 2015), which provide information not only on pure terrain properties, but also on other environmental parameters. Flow line curvature, general curvature, real surface area and vector ruggedness characterize the morphometry. Relative slope position index and topographic position index are in connection with topographic situation. Channel network base level, mass balance index, MRVBF (multiresolution index of valley bottom flatness), MRRTF (multiresolution index of the ridge top flatness), stream power index, vertical distance to channel network are in connection with the hydrological and run-off properties of the area. Diurnal anisotropic heating and SAGA wetness index are in relation with microclimate.

Imagery provided by satellite remote sensing provides direct or indirect spatial information on land cover, land use, vegetation condition and bare soils. For the modelling, satellite images from the Moderate-Resolution Imaging Spectroradiometer (MODIS) sensor were used, which were acquired in spring and fall in line with plant phenology. Data from the red (R) and the near infra-red (NIR) bands and NDVI (Normalized Difference Vegetation Index) were applied. Very recently a red band, cloud-free Sentinel-2 image mosaic has been created, which covers the whole area of Hungary, by the seamless mosaic of more than 30 images acquired in November-December 2016. These above listed remotely sensed variables were selected due to their potential information content on the state of vegetation and biomass, which indicates also certain soil features. We reviewed in a paper (***Pásztor & Takács 2014***) how remote sensing can concretely aid to solve the problems posed by soil mapping and its operational practice. Land use was taken from the CORINE Land Cover 1:50,000 (CLC50; Büttner et al. 2004), which is a national land cover database elaborated on the basis of the CORINE nomenclature of the European Environment Agency, and adapted to fit the characteristics of Hungary. The main objective of this approach is to improve the predictive applicability of remotely sensed information.

Lithology was derived from the Geological Map of Hungary 1:100,000 (Gyalog & Síkhegyi, 2005). In order to simplify the large number of lithology and facies categories, units were correlated with the nomenclature of parent material defined in the FAO Guidelines for soil description. The FAO three-level hierarchic code system (FAO, 2006) was used to achieve correlation between the geological formations and the relevant parent material classes. The focus was on the unconsolidated parent materials, because of the extensive area of quaternary sediments (***Bakacsi et al., 2014****)*. The groundwater level was taken from the Geological Atlas of Hungary (Pentelényi & Scharek, 2006). This polygon based map displays rather broad interval categories, not continuous depth.

Since SCORPAN equation (base equation of DSM) includes other or previously measured properties of soil, the usage of spatial, legacy soil data efficiently supports the applicability of DSM and improves the accuracy of DSM products as well *(****Pásztor et al., 2016****)*. In DOSoReMI.hu we heavily relied on the soil mapping units of DKSIS and some further former thematic soil maps.

Table 1. List of environmental covariates used in DOSoReMI activities.

Factors	Name	Resolution
Soil	Genetic soil map of Hungary	1:200,000
	DKSIS: soil physics SMU*	1:25,000
	DKSIS: soil chemistry SMU*	1:25,000
Climate	Mean annual evapotranspiration	100 m
	Mean annual evaporation	100 m
	Mean annual precipitation	100 m
	Mean annual temperature	100 m
Organism	MODIS: NDVI	250 m
	MODIS: Near infrared band	250 m
	MODIS: Red band	250 m
	SENTINEL Red band	10 m
	CORINE Land Cover	1:50,000
Relief	Altitude	100 m
	Aspect	100 m
	Channel network base level	100 m
	Cross-sectional curvature	100 m
	Diffuse insolation	100 m
	Direct insolation	100 m
	Diurnal anisotropic heating	100 m
	Downslope curvature	100 m
	Local curvature	100 m
	Local downslope curvature	100 m
	Local upslope curvature	100 m
	Longitudinal curvature	100 m
	LS factor	100 m
	Mass balance index	100 m
	MRRTF	100 m
	MRVBF	100 m
	Relative slope position	100 m
	Saga wetness index	100 m
	Slope	100 m
	Stream power index	100 m
	Surface area	100 m
	Topographic position index	100 m
	Topographic wetness index	100 m
	Upslope curvature	100 m
	Vertical distance to channel network	100 m
Parent material	Geological map of Hungary	1:100,000
	Groundwater	1:100,000

* soil mapping unit

The raw auxiliary dataset was subjected to certain pre-processing prior to its usage in various spatial inferences. The maps of covariables were converted to rasters with 100 m spatial resolution. The DEM and its derivatives as well as the satellite images and meteorological layers were resampled, the vector data were rasterized to the standardized 100 m resolution grid. The categorical data (land cover, geology, groundwater and soil mapping units by properties) were used in indicator form. They were split into separate layers by their attribute and given a binary code for presence or absence. To reduce the number of predictor variables in a specific spatial prediction and to avoid their multicollinearity, principal component analysis (PCA) was carried out. In the further analysis, the first principal components, which explain together 99% of the variance, were used.

Spatial inference and accuracy assessement

Spatial inference of reference data has been carried out using a variety of geostatistical and data mining tools: co-kriging with external drift, regression kriging, sequential stochastic simulation, classification and regression trees, random forests, quantile regression forests. Primary soil property maps were typically produced using regression kriging (RK). In the case of further soil features the applied method for the spatial inference of a specific target variable was suitably selected: essentially regression and classification trees as well as random forest for categorical data, indicator kriging for probabilistic management of criterion type information. Application of a geostatistical (namely sequential stochastic simulation based on regression kriging; ***Szatmári et al., 2015***) and a machine learning (namely classification trees; ***Laborczi et al., 2016***) method for specific mapping purpose was published. We also reviewed in a paper (***Szatmári & Pásztor 2016***) how geostatistics contributed to the evolution of and relied on in DSM.

In addition to provide pure spatial prediction, its uncertainty has been also modelled by detailed accuracy assessment. Both global and local uncertainty have been targeted. Local uncertainty of RK originated maps was estimated by kriging variance. In the case of soil class maps various measures of classification results were used. Global accuracy was assessed either by using independent soil information (that is inference was based on one reference soil observation data set, while another was used for validation) or checked by Leave-One-Out-Cross Validation (LOOCV; Stone 1974). In the cases of numerical variables, overall accuracy was expressed by the following parameters: mean error (ME), mean absolute error (MAE), root mean square error (RMSE) and root mean normalized square error (RMNSE). For soil class maps overall accuracy and overall kappa (Cohen, 1960; Rossiter, 2004) were used.

The targeted soil properties have been multi-mapped by the aid of selected sets (i) of reference data, (ii) spatial auxiliary information and (iii) inference methods. Optimized products have been achieved by iteration, which is based on the results of accuracy assessment supplemented with the evaluation of the implemented resources.

Target theme selection

The national and international requirements on Hungarian, nationwide, regionalized soil data was evaluated and ranked according to their social benefits. Soil property and class maps have been compiled partly according to GSM.net specifications, partly by slightly or more strictly changing some of their predefined parameters (depth intervals, pixel size, property etc.) according to the specific demands on the final products (Table 2).

Table 2. Systematic grouping of the potential target variables according to DOSoReMI.hu framework

TARGET VARIABLE					
PRIMARY SOIL PROPERTY			**SOIL CLASS**		
whole	*layer*		*whole*	*layer*	
soil profile	*GSM.net standard*	*specific depths*	*soil profile*	*GSM.net standard*	*specific depths*
standard or unique feature			standard or unique feature		
SECONDARY SOIL PROPERTY			**SECONDARY SOIL CLASS**		
whole	*layer*		*whole*	*layer*	
soil profile	*GSM.net standard*	*specific depths*	*soil profile*	*GSM.net standard*	*specific depths*
standard or unique feature			standard or unique feature		
SOIL FUNCTIONS, SERVICES					

Main results

The main result of DOSoReMI.hu is a collection of spatial soil information in the form of unique digital soil map products (in a more general meaning), which were optimally elaborated for the regionalization of specific soil (related) features. Significant part of them were never mapped before, even nationally with high (~1 ha) spatial resolution.

Numerous primary soil property maps (rootable depth, texture, fractions %, water content at field capacity, SOM, CaCO3 content, pH) have been compiled with proper DSM techniques. Each target variable was modelled by a sequence of spatial inference approaches (altering either methods or the reference and predictor data), which were always accompanied by detailed accuracy assessment for the determination of the best performing set of soil data, method and auxiliary covariables for the given target variable. Some of the elaborated maps have been further utilized to take steps for the regionalization of higher level soil information (secondary properties, functions, services).

A national soil type map with harmonized legend as well as with spatially relatively homogeneous predictive power and accuracy was also targeted. Several approaches were tested and integrated to produce the map (***Pásztor et al., 2018***). We introduced a Modified Random Forest method by a sequential applications of random sampling of nationwide soil type maps, which were used in CART analysis; producing class map based on maximum-likelihood decisions. A synthetic, geo-referenced TIFF image, consisting of the predictor variables as image bands were created. A sequence of multi-resolution segmentations were applied on the image layers to delineate homogeneous spatial entities that were used later as objects for classifications. We introduced a sequential classification approach. Evaluation of the results showed that the object based, multi-level mapping approach performs significantly better than the simple classification techniques.

For the support of certain nationwide spatial delineation problems some very special soil features were also regionalized, which were never mapped before in this form. The spatial inference of diagnostic features like: maximal pH in the upper 150 centimeter; average, weighted salt content in the profile; vertic property in the upper 100 cemtimeter; gleyic features in the upper 40 centimeters; etc. required multiple and successive approximations. The final products were used in the delineation of areas with natural constraints and identification of areas suitable for irrigation from pedological point of views (***Pásztor et al., 2017d***).

Map production was not formerly supplemented by accuracy assessment. The newly produced digital soil information and maps are supplied with the estimation of both local and global uncertainty, reliability. The assessment of local uncertainty of the prediction makes the application of an inset map possible for the expression of the inherent vagueness of spatial prediction in the layout of the compiled spatial soil information for the visualization of the reliability of the deduced prediction. In addition to local uncertainty, global accuracy is also communicated by certain measures of the results. The cartographed map products also display metadata related to the set of reference data, predictors and the applied method.

Table 3 is a snapshot listing the compiled map products containing information on some of their basic features: thematic and depth representation, reference soil dataset and global accuracy expressed by RMSE or overall accuracy.

Table 3. Global accuracy expressed by root mean square error or overall accuracy values of the finalized maps produced in the frame of DOSoReMi.hu. The reference soil data sets used in the best performing spatial inference are denoted by superscript letters.

	GSM.net depth intervals (cm)						Equidistant depths (cm)		
Soil properties	0-5	5-15	15-30	30-60	60-100	100-200	0-30	30-60	60-90
Soil organic matter (%)	-	-	-	-	-	-	1.0[a,b,c]	-	-
Soil organic carbon (tons/ha)	-	-	-	-	-	-	10.4[a]	-	-
pH (-)	-	-	-	-	-	-	0.7[a,b]	-	-
Electrical conductivity (dS/m)	-	-	-	-	-	-	1.4[b]	-	-
Bulk density (g/cm^3)	-	-	-	-	-	-	0.2[a]	-	-
Sand (%)	17.4[a]	17.0[a]	16.9[a]	17.0[a]	19.7[a]	23.3[a]	16.3[a]	17.0[a]	-
Silt (%)	14.2[a]	13.6[a]	13.1[a]	12.7[a]	14.9[a]	18.6[a]	13.1[a]	12.7[a]	-
Clay (%)	10.0[a]	9.6[a]	9.2[a]	9.3[a]	10.4[a]	11.0[a]	8.9[a]	9.3[a]	-
Texture class (USDA)	83%*	84%*	84%*	83%*	81%*	80%*	85%*	83%*	
With specific or unique depth(s)									
Rooting depth (cm)	31.3[a]	(*No depth specification*)							
Soil type map (Hungarian Classification)	70%*	(*No depth specification*)							
Exchangable Sodium Percentage (%)	21.6[b,d]	(0-100 cm)							
Coarse material (%)	19.8[a]	(0-100 cm)							
Maximum pH in the soil profiles (-)	0.8[b]	(0-150 cm)							

a: Hungarian Soil Information and Monitoring System, b: Digital Kreybig Soil Information System, c: Soil Fertility Monitoring System, d: Hungarian Detailed Soil Hydrophysical Database.

* overall accuracy

The map products are published on the www.dosoremi.hu website and are serviced in two different way. In the atlas version, map layouts are collected and published for application as graphical elements. Interactive maps are produced for browsing over alternative base map background. Most relevant information on the compilation and applicability of the maps are also communicated on the site and supplemented with a slideshow and a review paper (***Pásztor et al., 2017b***)on the elaboration and interpretation of the renewed Hungarian Spatial Soil Data Infrastructure.

The maps elaborated according to GSM specifications represent the Hungarian contribution to the GlobalSoilMap.net project (***Pásztor et al., 2017c***). Further map products are also under development in the follow up of DOSoReMI.hu to contribute to other worldwide activities, like GSOC17. Based on more extended data infrastructure, it is suggested that national initiatives could produce more accurate and reliable products. A comparative study was carried out for the evaluation of the differences between maps which are aggregated from standard GSM layers (0-5 cm, 5-15 cm, 15-30 cm) and those which were created directly for the same, entire layer (0-30) (***Laborczi et al., 2017***). The maps compiled by the two approaches have statistically demonstrable differences and the usage of the directly computed map is recommended against the synthetized map.

Six newly compiled digital soil maps (soil type according to the traditional classification system as well as to WRB reference soil groups, SOM, texture, pH, productivity) were selected to represent the country's soil cover in the recently edited ***National Atlas of Hungary (2017)***. The maps were properly interpreted and generalized to fit the atlas standard requirements. The experiments gained during our national mapping activities were further utilized at European level for the elaboration of 3D hydraulic database (***Tóth et. al., 2017***).

Supplementary results

Pilot study for the analysis of the effects of the various DSM components on the accuracy of the output maps
Prior to the management of countrywide challenges we carried out comprehensive analysis of the effects of the various DSM components on the accuracy of the output maps in a selected pilot area. We digitally mapped the agri-environmental conditions in Zala county for its whole territory at a resolution of 20. The various soil characteristics were mapped in different ways. Regression kriging, classification trees, maximum likelihood clustering, universal kriging were tested. The resulted maps proved to be unique in themselves, since never before the whole area of the county was mapped for these properties with similar spatial resolution (***Illés et al., 2014***). The most detailed analysis was carried out for the topsoil SOM using regression kriging and published in ***Szatmári et al. (2013)*** and ***Pásztor et al. (2014c)***.

Disaggergation of category type soil maps to improve their spatial resolution
We tested the applicability of decision trees and random forests as suitable spatial data mining tools to increase the spatial resolution of category type soil maps. The approach was induced by the fact, that certain thematic soil maps are not available in the required scale. Machine learning approaches were applied to understand the soil-landscape models involved in existing soil maps, for the posterior formalization of the survey/compilation rules. The identified relationships expressed in decision rules made the creation of spatially refined maps possible by the aid of high resolution environmental auxiliary variables. Larger scale, spatial soil information played a special role among these co-variables. Our results were published in ***Pásztor et al. (2013 and 2014a)*** and ***Laborczi et al. (2015)***.

Usage of legacy soil data in DSM
Development of DSM can be notably attributed to frequent limitations in the availability of proper soil information; consequently it has been typically used in cases featured by limited soil data. Since SCORPAN equation (base equation of DSM) includes other or previously measured properties of soil, the usage of spatial legacy soil data supports the applicability of DSM and improves the accuracy of DSM products as well. Nevertheless the occurrent abundance of available soil information poses new demands on and at the same time opens new possibilities in the application of DSM methods. Three approaches were conceptualized in ***Pásztor et al. (2016a)*** for the application of Hungary's most extended legacy soil data source in goal oriented digital soil mapping: (i) application of DKSIS SMUs in regression kriging; (ii) disaggregation of categorical soil maps with the aid of auxiliary spatial soil information; (iii) extension of the spatial validity of sparse soil profile data based on the homosoil concept. They were successfully applied in various DOSoReMI.hu mapping activities.

Optimization of sampling design for digital soil mapping
The capabilities of spatial simulated annealing (SSA) sampling optimization algorithm (using regression kriging prediction-error variance as optimization criterion) were tested and proved to be a useful tool for the optimization of sampling design for digital soil mapping considering demands and constraints (e.g. the expectation of the accuracy and/or uncertainty of the prediction(s), taking auxiliary information and/or previously collected samples into account, the number of new observations, inaccessible areas for sampling, budget and/or accuracy constraints etc.). The results

of the studies showed that, SSA can solve the recent issues of spatial soil sampling for digital soil mapping. Moreover, we have extended the SSA methodology to be able to simultaneously optimize the sampling design for more than one soil variable using the combined regression structure of the given soil variables and the variogram model of the dominant parameter. The results were published in ***Szatmári et al. (2015; 2016; 2017)***.

Digital mapping of specific soil and land features
Following a pilot study (***Négyesi et al, 2014***) wind erosion susceptibility of the Hungarian soils was mapped on national level integrating three pillars of the complex phenomenon of deflation (***Pásztor et al., 2016c***). Results of wind tunnel experiments on threshold wind velocity of huge amount of various and representative soil samples were used for the parametrization of the countrywide map of soil texture for the upper 5 centimeters. Average wind velocity was spatially estimated with 0.5' resolution using the MISH. The ratio of threshold wind velocity exceedance was determined based on values predicted by the soil texture map at the grid locations. Ratio values were further interpolated to a finer resolution using soil texture map as spatial co-variable. Land cover was taken into account for the compilation of the final susceptibility map. According to the resulted map, about 10% of the total area of Hungary can be identified as susceptible for wind erosion.

Soil erosion of Hungary was assessed by spatially explicit modelling producing up-to-date soil erosion map for the whole area of Hungary (***Pásztor et al. 2016e***). Universal Soil Loss Equation and the Pan-European Soil Erosion Risk Assessment models were combined in order to achieve a map that can be used by a wide range of professionals. The use of a harmonized input data set provided a base for comparison and synthesis of the two methods. Both the USLE and the PESERA models were applied for the year 2010. Due to the extreme precipitation rates of that year, the output layers of both models represent a worst case scenario from a climatic point of view for soil erosion potential. The C factor of maize was applied, which also represents a worst case scenario. In order to provide one unified map, a simple ensemble model was calculated. The results show that about 26% of the country's total area is prone to moderate to high erosion rates. The map supports previous studies, presenting a distribution of erosion risk that is similar to earlier works in both spatial patterns and magnitude, however the new map is spatially more detailed and the use of the best available data sets also makes it more reliable.

Inland excess water hazard in Szabolcs-Szatmár-Bereg county was regionalized and digitally mapped as in ordinary DSM, using auxiliary spatial environmental information (***Pásztor et al., 2104c***). Quantified parameters representing the effect of soil, geology, groundwater, land use and hydrometeorology on the formulation of inland excess water were defined and spatially explicitly derived. The complex role of relief was characterized by multiple derivatives of a proper DEM. Legacy maps displaying inland excess water events were used as reference. Spatial prediction was carried out using regression kriging. The result map is proposed to be used for numerous land related activities.

Geogen radon potential in Pest County was regionalized and digitally mapped as in ordinary DSM, using auxiliary spatial environmental information (***Pásztor et al., 2106d***). Regression kriging (RK) was applied for the interpolation using spatially exhaustive ancillary data on soil, geology, topography and climate. Overall accuracy of the map was tested by Leave-One-Out Cross-Validation. Furthermore the spatial reliability of the result map was also estimated by the calculation of the 90% prediction interval of the local prediction values. The area affected by large GRP risk is between 719 ha and 1,749 ha by 90% probability.

Application of the elaborated digital soil property maps for the support of spatial planning and land management was also studied (***Pásztor et al., 2017d***). Some aspects of mapping higher level, complex soil features (derived properties, functions, services) were addressed, presenting variations for their spatial assessment. We found:
- digital soil property maps provide great versatility for mapping higher level soil features;
- many opportunities are promised by their implementation in process modelling;
- target specific digital soil mapping can produce directly applicable products.

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*: Publications listed in bold were compiled in the frame and by the support of the research project K- 105167.