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Spatial assessment of the soil organic carbon content under different types of land use in the Ohrid valley

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Abstract

Spatial assessment of key soil properties is a basic prerequisite for the evidence-based decision making and sustainable use and management of soil. The aim of this work was to estimate the spatial distribution of SOC under different types of land use, by the means of Digital Soil Mapping techniques. A site-specific soil data collection for the Ohrid valley was integrated with continuous and discrete datasets of environmental covariates, serving as predictors. The selected test area outlines the variability of factors influencing the SOC content and spatial distribution. Soil sampling locations were randomly distributed within a predefined mesh with a 1-sq.km spatial resolution and further stratified to outline different types of land use within each mash square. Soil samples were collected from 93 locations at three depths, each 20 cm apart, covering the total area of 10 thousand ha of arable land, forestland, and land under natural vegetation. A set of additional environmental dataset was collected, namely the soil map, land use map, geology map, digital terrain model and its derivatives, satellite images, climate data, as well as a set of indices NDVI, SAVI, BI etc., developed from the remote sensing datasets. Multiple linear regression was used for evaluating the regression pattern between the environmental predictors and the target variable. To estimate spatial variability, several regression tree methods were used. The results obtained using this approach have given a better spatial overview of the most vulnerable areas regarding SOC depletion. Out of 21 locations examined, the content of soil organic carbon in the top layer (0-20 cm.) of forestland was on average 6.81%, while at 22 locations examined under grassland, the average content was 4.07%. The arable land, which is under continuous human impact, had the lowest content of SOC of 2.5% under field crops and 2.61% under perennials.

Key words: soil, carbon, mapping, modelling, remote sensing

Introduction

Soil organic carbon is important in relation to soil fertility, sustainable agricultural systems, and crop productivity, and there is a concern about its the levels in many soils, particularly with respect to global warming.

Soil organic carbon (SOC) is recognized as one of the most relevant indicators of soil quality (Bünemann et al., 2018) and land degradation (Lorenz et al., 2019) and is one of the most complex components of terrestrial ecosystems. It is essential for many vital soil functions, such as soil structure, aeration, nutrient storage, water-holding capacity, plant health, and productivity (Murphy, 2015) that can be grouped into three categories: physical, chemical, and biological (Fenton et al., 2008).

This essential element is actually one of the largest reservoirs of organic carbon on the global scale (Schlesinger, 1995; Eswaran et al., 2000). Therefore, carbon dioxide sequestration in plants and carbon storage in soil and biomass could be considered as a complementary solution against climate change.

Increased human activities, such as stock grazing, cultivation, deforestation, and plantations have substantially changed the carbon balance between soil and atmosphere and, thereby, mitigated or accelerated global climate change (Zhao et al., 2014). The change in quality and quantity of soil organic carbon inevitably affects various terrestrial ecosystem functions such as soil fertility, biological diversity, and biomass productivity (Kaiser et al., 2010).

Land-use change may lead to changes in the physical and chemical properties of soil through their influence on various ecological processes (Chen et al., 2010). The soil organic carbon is a relatively stable parameter that reflects the influence of management and crop types over periods of decades and is of essential importance for soil quality (Christensen and Johnston, 1997).

For these reasons there is a large interest in finding out the size of the carbon pool and its sequestration potential. In 2008, Bajtes stated that conventional methods using soil maps as a basis for soil carbon estimates had a limited number of soil observations (Minasny et al., 2013). In the past two decades the digital soil mapping technology has rapidly progressed, enabling soil carbon stock estimates over a large area. Owing to this approach, polygon-based soil maps are now replaced with digital maps of soil carbon content (Grunwald, 2009). Digital mapping of soil carbon enables us to estimate the baseline carbon levels crucial for prediction of carbon emissions/ removals, to identify variables controlling soil carbon, to validate mitigation potential, and to assist in natural resource management and monitoring.

The major goal of the present study is to analyze the effect of land-use change involving forest, arable land, perennial plantations, and pasture in the Ohrid region, the Republic of North Macedonia on the potential of soil carbon sequestration in terms of the concentration of soil organic carbon.

Material and Methods

The use of digital soil mapping for estimating soil organic carbon enables preparation of grid maps of a certain region, thus outlining spatial dynamics of certain soil properties and revealing regions prone to certain types of land degradation. Accuracy of such analysis mainly relies on the design of a field survey, laboratory testing, and predictors used.

There is no general rule for sample density and grid spacing in digital soil mapping (Minasny et.al., 2013); generally, the grid spacing decreases logarithmically with sampling density and vice versa. The sampling design pattern was a grid (1x1 km) which was additionally stratified in order to outline the current t land use/ land cover. The collection of soil samples was taken from 75 locations with corresponding spatial references (longitude, latitude, and altitude) during field work in the summer of 2020 in the Ohrid Lake region, following the LUCAS methodology. The sampling depth was 0-30 cm, with auger form 5 sampling points from each location (one central sampling point and 4 auxiliary sampling points at a 2 m distance). Additional data from each sampling location for the past and current land use and management practices applied were collected using a simple, semiquantitative description based on interviews with the farmers. In addition, site specific data for the natural co-variates, which might influence the SOC content, were collected as well.

Digital mapping was performed in the R software environment, in line with widely adopted approaches to estimating the spatial content of SOC in soil (FAO, 2018). Preprocessing of the predictors (environmental co-variables) was performed with the SAGA and QGIS software. Derivatives of digital elevation models (DEMs) and remotely sensed imagery (RSI) provide a dense grid of measured or interpolated values. In addition, six soil parameters (depth, carbonate, pH, clay, silt, and sand) were used as soil indices (SI1-SI6) and under two vegetation indices were used as predictors as well, e.g. the NDVI and Soil Adjusted Vegetation Index (SAVI).

The soil data set was transformed in order to get better distribution, and assigned with its spatial predictors. To estimate the spatial distribution of SOC, several linear regression models were tested. The best results were obtained with the Quantile Radom Forest regression model. The resolution of the graphical data sets used and derived output maps of SOC was 20 m.

Three quarters of all the samples (90) were used in the model as test data, while one quarter of 30 samples were used as a validation dataset.

In order to estimate whether the total SOC content is significantly different (calculated at 0.05 level) under different agricultural land-use types and management practices, the SPSS 20.0 programme package was used for statistical analyses.

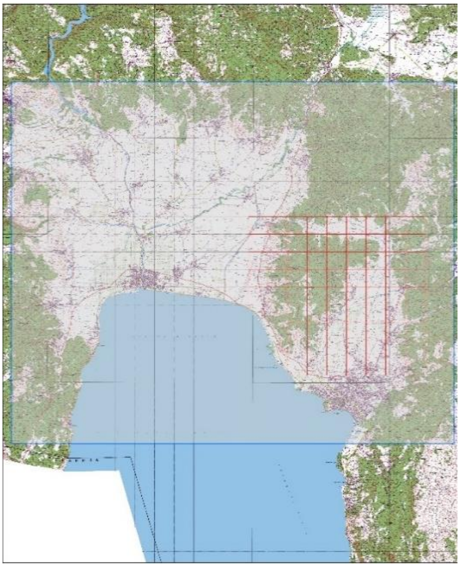


Figure 1. The Ohrid valley experimental site

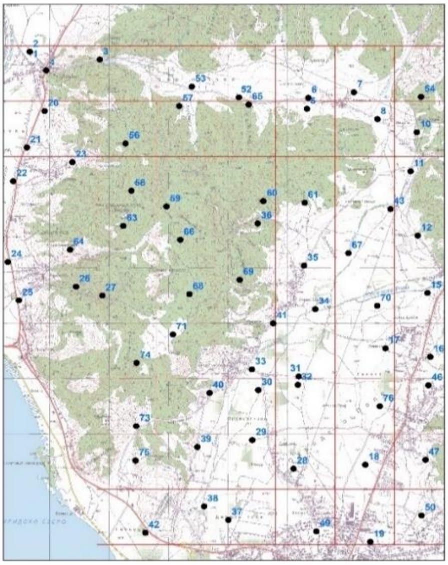


Figure 2. The Ohrid valley sampling points

Results and Discussion

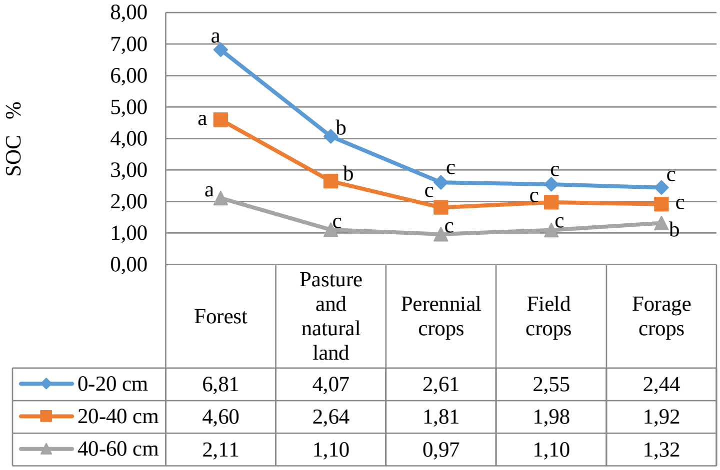
Recent investigations of SOC have shown the Ohrid region as one of the most vulnerable areas in the Republic of North Macedonia regarding the Soil Organic Carbon (SOC) dynamics.

Soil organic carbon content

Soil organic carbon (SOC) is a very dynamic and important component of fertile soil and serves as an indicator of the soil quality and health. Its content is closely related to natural conditions on one hand, and the human impact, on the other. While natural conditions are in a way more general and predictable to a certain extent, the human impact is local, very complex, variable and, in most cases, destructive. Farming systems have tended to mine the soil for nutrients and to reduce soil organic carbon levels through repetitive harvesting of crops and inadequate efforts to replenish nutrients and restore soil quality. In order to improve the prediction accuracy of SOC spatial distribution, the human impact should not be neglected.

Soils in cooler climates commonly have more organic carbon because of slower mineralization (decomposition) rates, which was confirmed with the results for this region. The Ohrid region has a moderate continental climate which is modified with the influence from the Ohrid lake, due to which winters are mild, while summers are more humid with lower average air temperatures. Precipitation in the region is higher than the country average. The results from this research indicate a high content of SOC in the Ohrid valley, which is mostly due to the favourable climate conditions.

The differences in the SOC content between various land-use types of the soils examined are clearly presented and shown in Figure 3.



	Forest	Pasture and natural land	Perennial crops	Field crops	Forage crops
0-20 cm	6,81	4,07	2,61	2,55	2,44
20-40 cm	4,60	2,64	1,81	1,98	1,92
40-60 cm	2,11	1,10	0,97	1,10	1,32

*Different letters (a, b, c) in the same line indicate statistically significant differences between land use at the probability level of $p < 0.05$

Figure 3. The content of soil organic carbon in the Ohrid region

All soils which are directly involved in the agricultural plant production are mainly classified as soils with a poor SOC content (1 to 3% SOC). In almost all cases the SOC content rapidly has decreased in the subsurface layers, hence in the layers of 20-40 and 40-60 cm it was below 1% (very poor content). The highest carbon concertation was under forests (6.81%) and pastures (4.07%), while the carbon content in the agricultural land was significantly lower, varying from 2.61 to 2.44% for perennial and annual crops, which is in line with the data reported by Gol (2009). The highest soil organic carbon content in natural forest found in this study can be due to regular addition of plant material including the above and below ground plant parts, and limited disturbances like grazing, logging, etc. (Steinbeiss et al., 2008). Compared to secondary forests, SOC stocks in 0-20 cm surface soils in shifting cultivation and rubber tree plantations (a 3-year-old plantation and a 7-year-old plantation) decreased by 34.0%, 33%, and 23% (Huang et al., 2014).

Management practices are another factor influencing the soil carbon content. Variations in soil carbon accumulation was reported to be proportional to the biomass input into the soil which, in turn, was largely dependent on plant biodiversity (Lambers et al., 2004). For these reasons, whenever possible, data were collected about the applied management practices (cultivation, irrigation, cropping patterns, etc.) and inputs (organic and mineral fertilizers, pesticides, etc.) at the selected sampling sites (Table 1).

Beside this, during the field survey, data for the natural co-variates, which might influence the SOC content such as the soil type, drainage, erosion intensity, soil depth, altitude aspect etc., were collected as well.

Table 1. Management types based on interviews

Agricultural land use		Management			
Management type	Crop	Tillage	Irrigation	Chemical fertilizer	Organic manure
Conventional	Field crops	+	-	+	-
	Perennial crops	+	+	+	+
	Forage crops	+	+	-	-
	Pasture	-	-	-	+

„+’’ means “yes or mostly”; „-‘’ means “no or hardly ever”

The organic carbon content in soils under intensive cultivation has been continuously declining for a long time until the improvement of management practice. Hence, carefully selected cropping or well-managed mixed crop-livestock systems are good examples of how soils can be improved and rebuilt.

Digital Soil Mapping

The concept of Digital Soil Mapping was formalized by McBratney et al. (2003) with the introduction of a predictive modelling approach “scorpan”, which is based on the previous works by Jenny and Dokuchaev. The concept of “scorpan” takes into account pedogenetic factors such as soil, climate, organisms, relief, parent materials, age, and spatial position for the prediction of soil attributes, formulated by the following equation:

$$S = f\,(s,c,o,r,r,p,a,n) + \varepsilon, \text{ or}$$
$$S = f\,(Q) + \varepsilon$$

Where S is the predicted soil attribute at an unvisited site, and can be predicted as a function of factors or environmental co-variables (Q) in a form of digital data in different formats and spatially depended residuals (ε) which are assumed to possess spatial structure. Therefore, to define the spatial trend of residuals, a kriging component is used to estimate the residuals at non-visited sites (Malone et al., 2017).

Such estimations as a part of geo-statistics are very practical and enable preparation of grid maps of a certain region which outlines spatial dynamics of certain soil properties and reveals regions prone to certain types of land degradation. Accuracy of such analysis mainly relies on the design of a field survey, laboratory testing, and predictors used.

In the process of preparing a model for SOC spatial distribution in the pilot area, a set of variables (predictors) in the form of continuous and categorical graphical raster data (Figure 4) were integrated with an auxiliary dataset of soil legacy data.

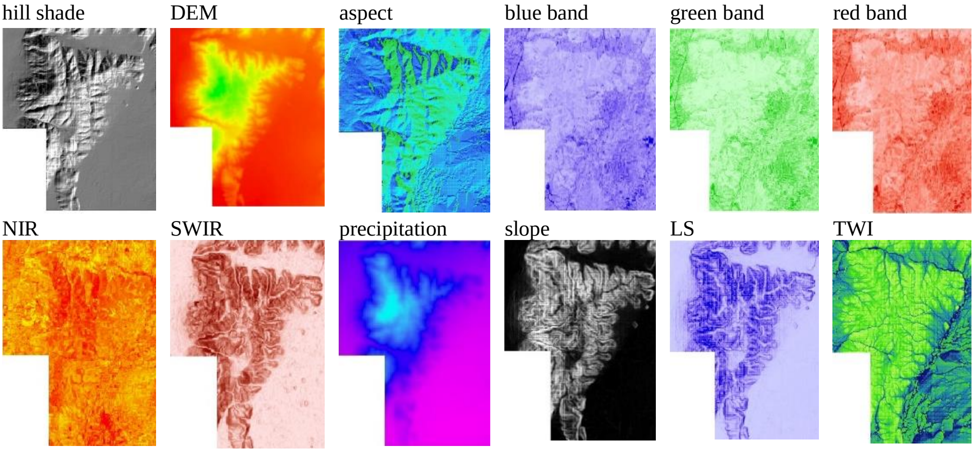
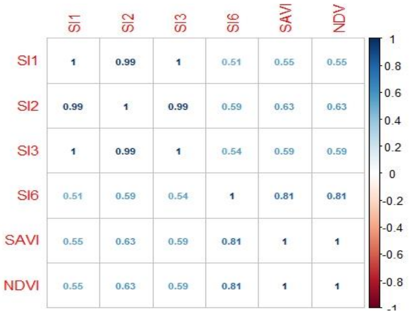


Figure 4. Enviromental variables

In order to evaluate the importance of each of the variables on the soil carbon dynamics, a correlation matrix has been prepared, which helped to eliminate certain indicators with low relevance.



	SI1	SI2	SI3	SI6	SAVI	NDV
SI1	1	0.99	1	0.51	0.55	0.55
SI2	0.99	1	0.99	0.59	0.63	0.63
SI3	1	0.99	1	0.54	0.59	0.59
SI6	0.51	0.59	0.54	1	0.81	0.81
SAVI	0.55	0.63	0.59	0.81	1	1
NDVI	0.55	0.63	0.59	0.81	1	1

Figure 5. A correlation matrix

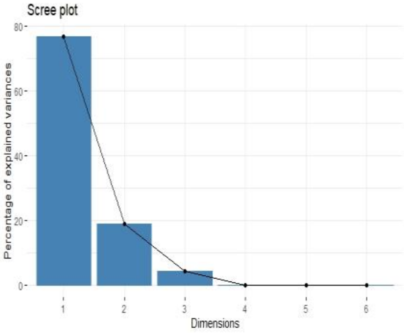


Figure 6. A principle component analysis (PCA)

A principal component analysis (PCA) was performed on the selected indicators and indices, and those PCs that explained the largest part of variability among the selected predictors were used for further modelling. In the case of the Ohrid region, the first 3 PCs have explained almost 100% of the variability of the predictors.

The results of modelled values for the spatial distribution of organic carbon in the soils of the Ohrid region are presented as a raster map (Figure 7 and 8), indicating the exact values which range between less than 2 up to more than 6%. The highest values of SOC, as expected, are in the mountainous part of the experimental site, covered with forests and natural vegetation, while the lowest content is in the soils in the central part of the valley and in the vicinity of the Gorno and Dolno Lakocerej villages.

Uncertainties are more pronounced in the areas under natural vegetation, which is most probably due to the change of land use (pastures, degraded, forest, bare land) at very short distances.

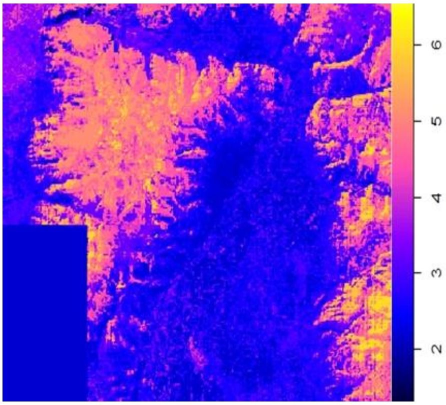


Figure 7. A soil organic carbon map - Ohrid

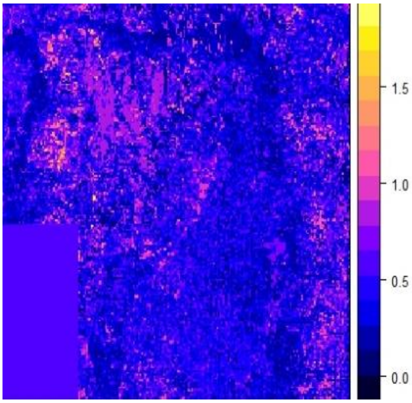


Figure 8. An uncertainty map of SOC - Ohrid

A correlation plot has been fitted for accuracy assessment between the modelled and measured data (Figure 9). The R-squared value has been at a satisfactory level (0.63) for such types of analysis when numerous variables included uses with various degrees of accuracy and resolution. For instance, the climate data compared to the terrain data were very rough. The predictors were, in fact, a mixture of continuous and discrete variables (the geology map, soil map, and LU/LUC map). All these aspects should be considered in the future when estimating the SOC spatial distribution for other regions, pilot sites, or the whole country.

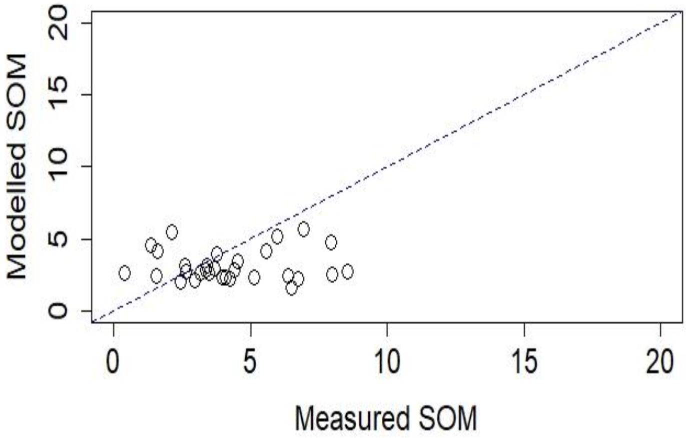


Figure 9. Accuracy assessment of the Ohrid samples

Land-use change may lead to significant effects on soil carbon concentration, which, in turn, has long-term effects on soil fertility and sustainability of the ecosystems (Bouwman, 1990).

Conclusion

As a general conclusion, it can be stated that the content of organic carbon in the arable (agricultural) land across the pilot region was at a worrying, low level.

The content of SOC has shown a decreasing trend for different land-use types, starting from the forest land with the highest content, to the arable land (especially field crops) as a category with the lowest content of SOC. All soils which are directly involved in the agricultural plant production are mainly classified as soils with the poor content (1 to 3% SOC). In almost all cases the content rapidly decreases in the subsurface layers, hence in the layers of 20-40 and 40-60 cm the content is below 1% (very poor SOC content). Agricultural producers can take many actions to improve and rebuild the SOC, especially soils that have been under cultivation for a long time. Each of them needs to introduce activities which should be based on the same principle aiming at increasing biomass production in order to build active organic matter and to store more carbon.

Acknowledgements

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Просторна процјена садржаја органског угљеника у земљишту на различитим типовима коришћења земљишта у Охридској долини

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Сажетак

Просторна процјена кључних својстава земљишта је основни предуслов за доношење одлука заснованих на доказима и одрживо коришћење и управљање земљиштем. Циљ овог рада је био да се процијени просторна дистрибуција органског земљишног угљеника на различитим типовима коришћења земљишта, помоћу техника дигиталног мапирања земљишта. Подаци о земљишту са више локација Охридске долине интегрисани су са континуираним и категоричким скуповима података који се односе на неке коваријате животне средине и који служе као предиктори. Одабрана област испитивања, омогућава да се добије добра варијабилност фактора који утичу на садржај и просторну дистрибуцију органског угљеника. Локације за узорковање тла су распоређене унутар унапријед дефинисане мреже са просторном резолуцијом од 1 км2 и су затим додатно стратификоване унутар сваке просторне јединице задате мреже, како би се обухватили доминантни типови коришћења земљишта. Узорци земљишта су прикупљени са 93 локације у три дубине на сваких 20 цм, на укупној површини од 10 хиљада ха ораница, шумских површина и земљишта под природном вегетацијом. Прикупљен је сет додатних података о животној средини: мапа земљишта, мапа коришћења земљишта, геолошка мапа, дигитални модел терена и његови продукти, сателитски снимци, климатски подаци као и сет вегетацијских индекса као на примјер: NDVI, SAVI, BI итд.. Мултифакторијална линеарна регресија је коришћена за процену обрасца регресије између предиктора животне средине и циљне варијабле. За процену просторне варијабилности коришћено је неколико метода регресионих стабала. Резултати добијени овим приступом дали су бољи просторни преглед за најугроженија подручја у погледу исцрпљивања органског угљеника. Садржај органског угљеника земљишта у горњем слоју (0-20 цм.) шумског земљишта, од 21 испитиване локације је у просјеку 6,81. %, док је на 22 испитиване локације под травњацима просјечан садржај био 4,07%. Обрадиво земљиште, које је под сталним утицајем човека, има најмањи садржај органског земљишног угљеника од 2,5% под ратарским културама и 2,61% у вишегодишњим засадима.

Кључне ријечи: земљишта, угљеник, мапирање, моделирање, даљинска детекција.

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