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Influence of terrain attributes on organic carbon stocks distribution in soil toposequences of central Poland

Abstract: The paper presents the results of research on the relationship between topography of undulated morainic plateau of postglacial landscape and distribution of organic carbon stocks in soil toposequences. The mean value of the soil organic carbon stocks (SOCS) for Retisols/Luvisols (RT/LV) was statistically lower than for the Phaeozems/Gleysols (PH/GL) but for RT/LV a higher variation of SOCS in comparison to PH/GL was observed. On the basis of Pearson correlation coefficient, the cartographic depth to water (DTW), the topographic wetness index (TWI) and the saga wetness index (SWI) were the most strongly correlated with the SOCS from among 13 analysed topographic attributes. In addition, the DTW was more correlated with SOCS than other topographic variables. Moreover, the DTW based on the channel networks with 2 ha flow initiation thresholds better correlate with SOCS than DTW obtained on the basis of channel networks with 1 ha and 4 ha flow initiation thresholds. Using Stepwise multiple regression analysis (SMLR), we concluded that the topographic attributes controlling the soil water content and slope shape had most impact on SOCS of the undulated morainic plateau of agricultural ecosystem. In this landform, where the RT/LV and PH/GL soil sequences dominate, the SOCS can be estimated by the DTW, TWI and GC (general curvature) with an estimation error of 0.21 kg m^{-2}. In view of the increasing availability of LiDAR data and power of GIS tools, the use of topographic metrics to assess spatial variability of soil properties will play an increasingly important role in the estimation of soil properties.

Keywords: soil organic carbon stocks, soil toposequence, terrain attributes, postglacial landscape, morainic plateau

INTRODUCTION

Soils play an important role in the global cycle of carbon via the accumulation and decomposition of soil organic carbon (SOC). Soil organic carbon stocks (SOCS) are about 3 and 4 times larger than atmospheric carbon and biotic carbon storages respectively (Lal 2004). The SOC contents and the SOCS have also a large impact on other physical and chemical properties, thus affecting soil quality. Therefore, the assessment of SOC and SOCS is of great importance (Qin et al. 2016).

In recent years, a range of techniques has been developed to predict and map SOC content and SOCS using the scheme of digital soil mapping (DSM) proposed by McBratney et al. (2003). Minasny et al. (2013) delivered a comprehensive review of the SOC content and the SOCS modelling for various scales and the DSM techniques. The development of GIS tools, the access to the LiDAR data and the progress of topographic metrics (attributes) allow better understanding of mechanisms underlying topographic impact on SOCS and other soil properties in agricultural ecosystems (Murphy et al. 2011, Li et al. 2018). Several studies have indicated that topography is one of the most important factors influencing the SOC and the SOCS, especially at regional and landscape

levels (Taghizadeh-Mehrjardi et al. 2016, Qin et al. 2016, Fissore et al. 2017, Zhu et al. 2017, Román-Sánchez et al. 2018, Li et al. 2018, Wang et at. 2018).

Numerous research results indicate that for mountainous landscapes, there is a relationship between the slope aspect and the SOC content and the SOCS (Qin et al. 2016, Zhu et al. 2017, Román-Sánchez et al. 2018). In turn, Drewnik et al. (2016) do not confirm this pattern for the Western Bieszczady Mountains (southeastern Poland). That the weak statistically significant tendencies concerning SOCS accumulated in soils of different altitudinal zones of the Karkonosze Mountains are due to inadequate sampling methodology was also stated by Szopka et al. 2016. Román-Sánchez et al. (2018) ranked topographic variables for the needs of modelling SOC content in mountain regions. They pointed out that, after insolation, the following variables had an impact on SOC content, curvature, TPI (topographic position index), SPI (steam power index) and slope gradient. In addition to remote sensing indices, Taghizadeh-Mehrjardi et al. (2016) used the topographic wetness index (TWI) and the slope gradient for piedmont hillslopes for modelling SOC content. The TWI, in addition to other topographic indices, has been successfully used to model SOC content in postglacial areas with various soil parent material (Obu

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http://ssa.ptg.sggw.pl/issues/2018/694

et al. 2017, Li et al. 2018, Wang et al. 2018). The TWI is effective in identifying wet areas and investigating slope water redistribution and thereby in the determination of spatial distributions of soil water content along slopes (Lang et al. 2013). Murphy et al. (2007) proposed a new topographic metric called the cartographic depth to water (DTW) for mapping wetland. This topographic index has a higher potential for applications in soil studies than the TWI (Murphy et al. 2009) because topographically depended soil properties are better correlated with the DTW in comparison to the TWI (Murphy et al. 2011).

The study objectives were: 1) to investigate the relationship between topography of postglacial landscape and organic carbon stocks distribution in agricultural field soil toposequences, 2) to use topographic variables to predict soil carbon stocks.

MATERIALS AND METHODS

The investigated area is located in the central part of the Poznań Lakeland, within an undulated morainic plateau bordered directly from the south by a hummocky morainic plateau formed on the hinterland of the maximum glacier range of the Poznań phase of Vistulian glaciation (Kasprzak 1988). The study area is located at about 30 km NE from the Poznań city (Fig. 1A). The spatial variability of soil properties were estimated on 100 ha arable field, being under long-term annual conventional tillage. Field work was carried out in two stages. In the first, soil variation was established by scatter-point method (pits and boreholes) and then the representative pedons were localized. In the second stage, the two transects (A and B) were delineated. In 52 open pits along the transects, the soil morphology was determined by identification of genetic and diagnostic horizons, boundaries between horizon sequences, soil colour, structure, consistency, reaction with hydrochloric acid as well as establishing taxonomic soil classification. From each soil horizon, the monolithic soil samples were collected for laboratory analyses and undisturbed soil samples were taken to determine the bulk density with four replications. Each the 52 pits were georeferenced with horizontal accuracy of 0.03 m by TC 500 Leica global positioning system (GPS) receivers. The
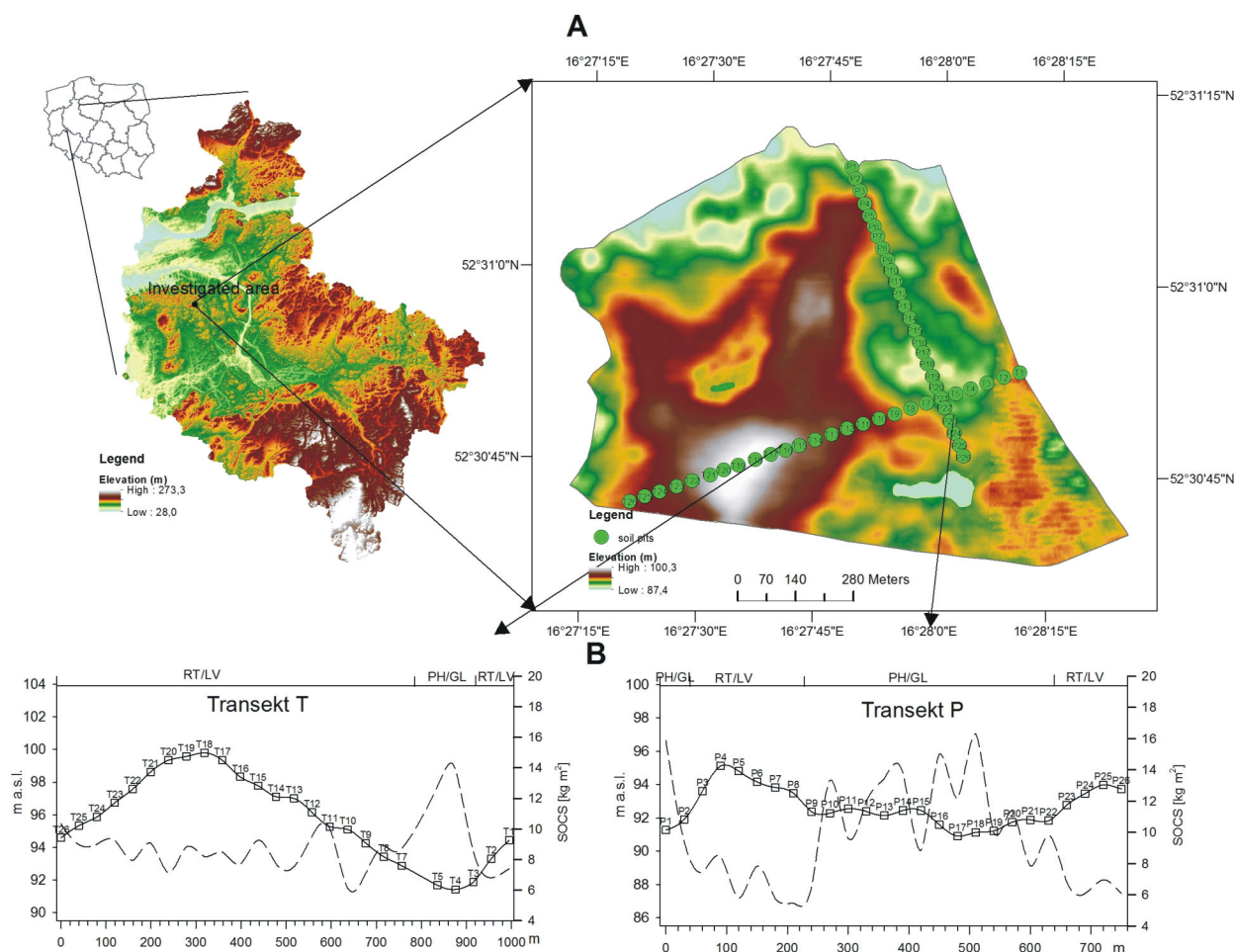

FIGURE 1. Location of investigated area (A) and the distribution jof SOCS in transects (B)

samples were air-dried and ground to pass through 2 mm sieve prior to analysis. In laboratory studies, the silt and clay fractions were determined by the areometric method, according to the Polish Standard PN-R-04032 (1998), while the sand particles were distinguished by the sieve method with wet fractioning. The division into textural classes was made according to the PTG (2009). The organic carbon content in fine earth was determined by wet oxidation with dichromate according to the Walkley-Black method (Nelson and Sommers 1982). To ensure the accuracy of the measurement results, all samples were analyzed three times and the data were averaged. The soil organic carbon stocks (SOCS) (kg m^{-2}), were calculated using the following equation (Román-Sánchez et al. 2018):

$$SOCS = \sum_{i=1}^{n} SOCC_i\, BD_i\, z_i\, 10^{-3}$$

were $SOCC_i$ is the organic carbon content (g kg^{-1}), BD_i is the bulk density (kg m^{-3}), and z_i is the horizon or layer thickness (m), i is the soil horizon or layer.

Topographic metrics (attributes) were derived from DEM with 5 m resolution created from LiDAR data. To reduce noise caused by local variation, the DEMs were filtered twice using a 5×5 low pass filter. The FILL function was used to generate a DEM free of depressions (Tarboton 1997). The filled DEM was then used to determine elevation, flow direction with D∞ algorithm (multiple flow direction), aspect, profile curvature (PrC), plan curvature (PlC), general curvature (GC), slope gradient, flow accumulation, topographic wetness index (TWI), SAGA wetness index (SWI), stream power index (SPI) and slope length factor (LS) (Beven et al. 1984, Moor et al. 1991, Tarboton 1997, Böehner and Selige 2006). In addition to the above-mentioned topographic metrics, the cartographic depth-to-water (DTW) was determined (Murphy et al. 2007). The DTW refers to the least-cost depth or elevation difference (in metres) to the nearest open water locations such as the DEM-derived streams, lakes, pools, ponds, or shoreline (Murphy et al., 2009; 2011). The DTW was calculated for channel networks with 4 ha (DTW$_4$), 2 ha (DTW$_2$) and 1 ha (DTW$_1$) flow initiation thresholds for the D∞ algorithm (single flow direction).

Statistical analyses for soil map units in the form of complexes (Soil Science Division Staff 2017) were performed using STATISTICA (version 13) (StatSoft, Inc., USA). In the two transects analyzed, the Retisols/Luvisols (RT/LV) and the Phaeozems/Gleysols (PH/GL) complexes were distinguished, which create a regular and repeating pattern on the landscape of undulated ground moraine. Each of the variables

(topographic metrics and SOCS) were tested for normality using the Kolmogorov-Smirnov test. Relationships between SOCS and topographic attributes were analyzed using the Pearson correlation coefficient (R). We also used the U Manna-Whitney'a test to determine the significant differences between the SOCS of the distinguished soil complexes as well as transects. This nonparametric test was used because within distinguished soil complexes/transects, though these being a grouping of variables, the SOCS did not show a normal distribution or the size of the sample of data was too small. Stepwise multiple regression analysis (SMLR) was used to study the statistical relationship between the SOCS and topographic factors, and to build a model that allows us to estimate SOCS based on topography metrics.

RESULTS AND DISCUSSION

The pedological cross-section presented in Figure 1 clearly shows that transects run through the terrain, which is diversified in terms of relief. In these transects, the Retisols/Luvisols (RT/LV) and the Phaeozems/Gleysols (PH/GL) create characteristic soil sequences along slopes which confirmed earlier observations within the Polish Lowlands (Marcinek and Wiślańska 1984, Komisarek 2000, Podlasiński 2013, Świtoniak 2014, Kozłowski and Komisarek 2016, Kozłowski et al. 2018). The relationship between SOCS values and the soil position in a relief is pronounced. The SOCS increased in pediments and depressions and decreased in summits and shoulders (Fig. 1B). In the RT/LV formed within higher part of slopes the SOCS values ranged from 4.3 to 11.6 kg m^{-2} and from 4.6 to 10.35 kg m^{-2} for transects P and T respectively. In soils occupying a lower position in the relief (PH/GL), the SOCS were clearly greater and ranged from 6.3 to 38.1 kg m^{-2}. Similar variation in SOCS values was obtained within sequence of erosional/colluvial soils located on Vistula Valley slopes (Świtoniak et al. 2015). Data presented in

TABLE 1. Basic statistics of the SOCS in transects P and T

Transect	Soil complex	Mean	Median	SD	CV
		kg·m^{-2}			%
P	RT/LV	7.2	6.1	2.2	30.5
	PH/GL	12.3	11.1	7.9	64.3
T	RT/LV	8.2	8.6	1.7	20.7
	PH/GL	12.1	12.8	3.2	26.7
P+T	RT/LV	7.9	8.1	1.9	23.9
	PH/GL	12.2	11.4	7.3	59.5

SD – the standard deviation, CV – the coefficient of variation.

Table 1 show that the PH/GL were characterized by a higher variation of the SOCS values than the RT/LV. In the RT/LV the coefficient of variation (CV) values of SOCS were 30.5% and 26.7% whereas in the PH/GL 64.3% and 26.7% for transect T and P respectively. In the transect P the mean SOCS were 7.2 kg m^{-2} for the RT/LV soils and 12.3 kg m^{-2} for the PH/GL soils whereas in the transect T the mean values of SOCS were 8.2 and 12.1 kg m^{-2} for the RT/LV and the PH/GL respectively. Both in the T and the P transect soils, statistically significant differences of the mean values of SOCS were found between the RT/LV and the PH/GL (Table 2). Statistical analysis did not show significant differences of the mean SOCS values of the RT/LV between the T and the S transects, as in the case of the PH/GL. The mean value of the SOCS for all analysed RT/LV of two transects was 7.9 kg m^{-2} whereas it was 12.2 kg m^{-2} for PH/GL.

Table 3 shows the basic statistical values of the topographical parameters of the analysed transects, while Figure 2 shows the spatial distribution of their values. The RT/LV have been formed in higher slope parts whereas the PH/GL in a lowest. The elevation for the RT/LV ranged from 93.27 to 100.30 m a.s.l. with the mean 96.16 m a.s.l. while for the PH/GL from 91.43 to 93.02 m a.s.l (the mean 92.32 m a.s.l). The mean slope gradient was a slightly higher for the PH/GL in comparison to the RT/LV. The values of DWT were higher for the RT/LV than for the PH/GL, both for DWT calculated on the basis of 1 ha, 2 ha and 4 ha flow initiation thresholds. This indicates that the PH/GL have been formed under poor drainage conditions caused by a shallow groundwater table (PSC 2011). The TWI and the SWI values were higher for the PH/GL than for the RT/LV. The mean vales of the TWI and the SWI of the RT/LV were 6.8 and 5.3, whereas for PH/GL 9.8, and 6.2, respectively.

A Pearson correlation analysis was performed to check the relationships between the Ln-transformed SOCS with the topographical variables (Table 4). The

TABLE 3. Basic statistics (mean – median and minimum – maximum) of topographic variables for RT/LV and PH/GL

Topography metrics	Soil complex	
	RT/LV	PH/GL
Elevation (m a.s.l.)	96.16–95.64	92.32–92.27
	93.27–100.30	91.43–93.02
Slope gradient (%)	2.8–2.7	0.4–5.3
	3.4–2.2	0.3–12.8
DWT1 (m)	3.0–2.8	0.4–5.3
	1.2–1.3	0.3–2.1
DWT2 (m)	4.6–4.9	2.6–2.4
	0.9–6.6	0.6–4.6
DWT4 (m)	4.3–4.5	2.6–2.4
	0.7–6.7	0.8–4.6
SWI (–)	5.3–5.3	6.2–6.3
	3.8–6.7	5.0–7.9
TWI (–)	6.8–6.5	9.8–9.4
	4.9–10.4	6.4–17.5
GC (–)	0.0009–0.0012	0.0025–0.0000
	-0.0248–0.0216	-0.0288–0.0752
PlC (–)	0.0125–0.0169	0.0003–0.0045
	-0.2731–0.4566	-0.1368–0.1624
SPI (–)	6.23–4.41	6.48–0.07
	0.10–17.48	0.01–64.42
Aspect (radians)	2.74–2.19	3.40–3.42
	0.06–6.21	0.11–6.24
LS (–)	0.1349–0.0005	0.1774–0.1843
	0.0002–1.7630	0.0874–0.3746

ln (natural logarithm)-transformed SOCS were most significantly correlated with all DTW (DTW_1, DTW_2, DTW_4) where the highest value of Pearson's correlation coefficient (R) was for the DTW_2 (R=-0.651) and the lowest for the DTW_1 (R=-0.553). These indicate that the DTW_2 based on the channel networks with 2 ha flow initiation thresholds better correlate with SOCS than DTW, obtained on the basis of the channel networks with 1 ha and 4 ha flow initiation thresholds. Murphy et al. (2011), analysing the relationship between DTW and soil types, soil drainage and other selected soil properties, including the soil carbon content, obtained the best correlation with the 4-ha flow-initiation DTW pattern. In addition to DTW in the analysed soil toposequences, there are significant relationships between SOCS, and TWI and SWI (R=0.573 and R=0.463, respectively). With an increase values of TWI, the SOCS of analysed toposequences show an increasing trend similar to

TABLE 2. The result of U Manna-Whitney'a test of the significant differences of the SOCS (statistical significance)

Transect	Soil complex	P		T		P+T	
		RT/LV	PH/GL	RT/LV	PH/GL	RT/LV	PH/GL
P	RT/LV						
	PH/GL	0.0014*					
T	RT/LV	0.0687	0.0042*				
	PH/GL	0.0343*	0.9783	0.0241*			
P+T	RT/LV	–	–	–	–		
	PH/GL	–	–	–	–	0.0014*	

*statistical significance.

TABLE 4. Correlation coefficients between terrain variables and SOCS

Terrain attributes												
	Elevation	Slope	DWT1	DWT2	DWT4	SWI	TWI	GC	PlC	PrC	SPI	Aspect	LS
SOCS	-0.380*	0.209	-0.570*	-0.651*	-0.637*	0.463*	0.573*	0.315*	-0.024	0.339*	0.028	0.082	0.102

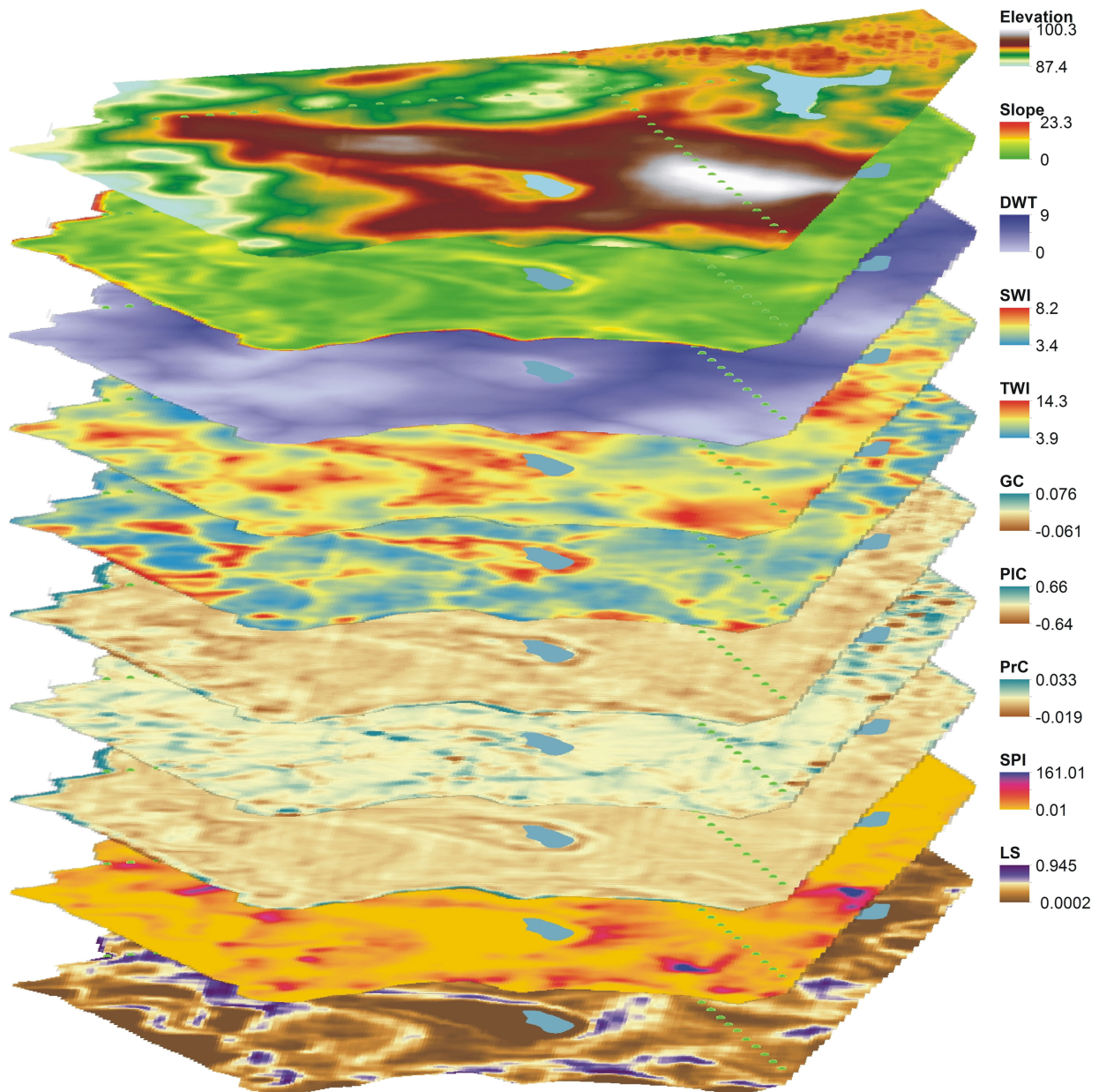*statistical significant at a level of significance 0.05.

FIGURE 2. Spatial distribution of basic topographic attributes

that of DTW. The TWI is effective at identifying wetlands and investigating spatial distributions of soil moisture along slopes (Lang et al. 2013). Li et al. (2018), Wang et al. (2018) also found positive correlation between SOCS and TWI. Xin et al. (2016) in their studies conducted in Luoyugou watershed gully-hill of the Chinese Loess Plateau do not confirm these pattern but the soils of this area have been profoundly disturbed by human activity, particularly by the conversion from sloped land to terraced cropland. In turn, Murphy et al. (2009) suggest that DTW has a higher potential for applications in soil researches than TWI because most of soil properties topographically depended, are more correlated with

DTW than with TWI (Murphy et al. 2011). In our study, significant relations were also found between Elevation, PrC and GC and SOC stocks but these dependencies have correlation coefficient values lower (-0.380, 0.339 and 0.315 respectively) than those obtained for DTW and TWI. Despite this, these coefficients were statistically significant and indicate that the slope shape expressed by PrC and GC has

TABLE 5. The model parameters of SOCS (kg m^{-2}) prediction and standardized regression coefficient of topographic variables

Model	R^2	SE kg m^2
SOCS= 2.0532-0.0614 DTW2+0.045 TWI+5.884 GC	0.673	0.21
Standardized regression coefficient		

DTW$_2$	TWI	GC
-0.441	0.361	0.200

SE – estimate standard error.

also impact on SOCS. Insignificant linear correlations were observed between SOCS and Aspect, Slope, LS, PIC and SPI indicating that these topographic attributes were likely not an efficient controller of SOCS within analysed soils. In turn, Li et al. (2018) observed significant correlations between SOCS and Slope, GC, LS, PIC, PrC and SPI. Qin et al. (2016) and Zhu et al. (2017) for mountain terrain concluded that the aspect has a significant impact on the SOC content and SOC stocks. Drewnik et al. (2016) on the basis on research carried out in the Western Bieszczady Mountains (southeastern Poland) deduced that insolation, directly the slope exposure depended, was not the main reason for the differentiation of SOCS between the south and north-facing slopes.

Using the stepwise multiple linear regression analysis (SMLR), we built up model with ln-transformed SOCS as dependent variables. For this analysis, all the topographic attributes were taken as independent variables. The result indicates that only three variables, i.e. DTW$_2$, TWI and GC were statistically significant topographical variables allowing the estimation of SOCS in analysed soil sequences (Table 5). Among them, DTW had larger share in the estimation of SOCS rather than TWI and GC, as evidenced by the values of standardized regression coefficient. The SMLR model explains 67% of SOCS variability in analysed soils of toposequences with an estimation error of 0.21 kg m^{-2}. In our study, we indicated the possibility of estimating SOCS on the basis of topographic attributes for the soil landscape of undulating ground moraine made of boulder clay where the Retisols/Luvisols (RT/LV) and the Phaeozems/Gleysols (PH/GL) create characteristic soil sequences. Li et al. (2018) and Wang et al. (2018) modelled SOCS based on topographic variables and using the SMLR received the value of the determination coefficient similar to this obtained in our study. Wang et al. (2018) used independent variables such as Aspect, Elevation, Slope, TWI, CA (Catchment Area) and Landsat TM bands (B3, B4 and B5) while Li et al. (2018) used TWI, FPL (Flow Path Length), GC, Slope, LS, DI (Downslope Index), RePC1 and RePC2

(topographic relief component 1 and 2, respectively) to estimate SOCS. This indicates the need for further researches into the impact of topography on SOCS for various landforms. In addition, the development of GIS tools, the availability of LiDAR data and the improvement of topographic variables will allow better understanding of mechanisms underlying topographic impact on SOCS and other soil properties in agricultural ecosystems (Murphy et al. 2011, Li et al. 2018).

CONCLUSIONS

In this study, we investigated the spatial distribution SOC stocks within undulating ground moraine of Poznań Lakeland in relation to topographic attributes. The research was conducted in the soils of two transects running through undulated moraine plateau where the Retisols/Luvisols (RT/LV) and the Phaeozems/Gleysols (PH/GL) form a regular and repetitive patterns.

The mean value of SOCS for all analyzed RT/LV was statistically lower than for PH/GL but for RT/LV a higher variation of SOCS in comparison to PH/GL was observed. In summary, obtained results suggest that the topography significantly impacts spatial patterns of soil variability and resulting SOCS distribution. From a general perspective, we have shown that the DTW, TWI and SWI were the most strongly correlated with the SOCS from the analysed topographic attributes. In addition, the DTW was more correlated with SOCS than other topographic variables. Moreover, the DTW based on the channel networks with 2 ha flow initiation thresholds better correlate with SOCS than DTW obtained on the basis of the channel networks with 1 ha and 4 ha flow initiation thresholds.

The topographic attributes controlling the soil water content and a slope shape mainly had an impact on SOCS of agricultural ecosystem of undulated morainic plateau. In this landform, where the RT/LV and PH/GL had been formed, the SOCS can be estimated by DTW, TWI and GC with an estimation error of 0.21 kg m^{-2}. In view of the increasing availa-

bility of LiDAR data and the increasing power of GIS tools, detailed relations between soil properties and topographic metrics will play an increasingly important role.

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Wpływ atrybutów topograficznych na kształtowanie się zasobów węgla organicznego w glebach układu toposekwencyjnych w centralnej Polsce

Streszczenie: W pracy przedstawiono wyniki badań nad zależnością pomiędzy topografią polodowcowego krajobrazu falistej wysoczyzny morenowej a rozmieszczeniem zasobów węgla organicznego w glebach układów toposekwencyjnych. Średnia wielkość zasobów węgla organicznego w glebach (SOCS) Retisols/Luvisols (RT/LV) była statystycznie niższa niż w glebach Phaeozems/Gleysols (PH/GL), ale w RT/LV obserwowano wyższą zmienność SOCS w porównaniu z PH/GL. Na podstawie wartości współczynnika korelacji Pearsona, kartograficzna głębokość wód gruntowych (DTW), topograficzny wskaźnik wilgotności (TWI) i wskaźnik wilgotności SAGA (SWI) były najsilniej skorelowane z SOCS spośród 13 analizowanych atrybutów topograficznych. Ponadto DTW była bardziej skorelowana z SOCS niż inne zmienne topograficzne. DTW obliczona dla sieci cieków generowanych przy 2 ha akumulacji spływu wody koreluje lepiej z SOCS niż DTW uzyskana na podstawie sieci cieków z 1 ha i 4 ha progami ich inicjacji. Wykorzystując analizę regresji wielokrotnej krokowej postępującej (SMLR), wykazano, że atrybuty topograficzne charakteryzujące potencjalne warunki wilgotnościowe terenu i kształt stoków, miały główny wpływ na rozkład SOCS w falistej morenie dennej. W tej formie terenu, gdzie dominują sekwencje RT/LV i PH/GL, SOCS mogą być oszacowany na podstawie DTW, TWI i GC (całkowita krzywizna stoku) z błędem oszacowania 0,21 kg·m^{-2}. W związku z rosnącą dostępnością danych LiDAR i postępującą siłą narzędzi GIS, coraz ważniejszą rolę będzie odgrywać użycie wskaźników topograficznych do oceny przestrzennego zróżnicowania właściwości gleb i do oszacowania ich wielkości.

Słowa kluczowe: zasoby węgla organicznego, toposekwencja gleb, wskaźniki topograficzne, krajobraz polodowcowy, wysoczyzna morenowa