Simulation of Soil Organic Carbon Changes in Slovak Arable Land and their Environmental Aspects

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Abstract: One of the key goals of the Thematic Strategy for Soil Protection is to maintain and improve soil organic carbon (SOC) stocks. A decline of SOC stocks is politically perceived as a serious threat to soil quality and functions. A suitable tool for acquiring the information on SOC stock changes is modelling. The RothC-26.3 model was applied for long-term modelling (1970–2007) of the SOC stock in the topsoil of croplands of Slovakia. Simulation results show a gradual increase in the SOC stock in the first phase of modelling (1970–1995) mainly due to higher carbon input in the soil. A significant linear correlation ($r = 0.4^{**}$, $n = 275$) was found between carbon input and the final simulation of SOC stock. A close relationship between the SOC stock and soil production potential index representing the official basis for soil quality assessment in Slovakia was also determined and a polynomial relationship was found which describes the relation at the 95% confidence level. We have concluded from the results that balanced or positive changes in the SOC stock dynamics that are important for sustainable use of soils could be influenced positively or negatively in Slovakia by political decisions concerning the soil management. Moreover, the soil production potential index can be used as soil quality information support for such decision-making.

Keywords: agricultural management; long-term simulation; RothC model; soil organic carbon; soil quality

An interest in soil organic carbon (SOC) is common to soil scientists and related practitioners because of its importance for principle physical, chemical, biological and soil ecological functions and because SOC is a universal indicator of soil quality (Andrews *et al.* 2004; Ogle & Paustian 2005; Stolbovoy *et al.* 2007). Consequently, as variations in SOC levels can have serious implications for many environmental processes such as soil fertility, erosion and greenhouse gas fluxes, the need to estimate SOC changes has become fundamental to several pan-European and global environmental policies. At a European level, the SOC is considered in many policies and strategies of the European Union. A decline of the SOC stocks in soils is politically perceived as a serious threat to soil quality and implicitly also to its ecological and environmental functions (EC 2006a; Eckleman *et al.* 2006; Stolbovoy *et al.* 2007; Stolbovoy & Montanarella 2008). The SOC stock is influenced by land use, particularly soil and crop management has a strong influence on SOC stocks in cropland (Ogle & Paustian 2005). Crop residues and farmyard manure input to the soil seem to be an important crop management option which influences the SOC stock balance in the soil

(Schulp & Verburg 2009; van Wesemael *et al.* 2010). Negative trends in the SOC stock balance can be treated politically via various measures taken in crop and soil management practices (e.g. Common Agricultural Policy, EC 2006b). Information on soil quality is essential for any decision-making on crop and soil management (EC 2006b). In Slovakia, the soil quality for decision-making needs is expressed by so called "soil production potential index" which is a complex functional characteristic of landscape attributed to soil-landscape units (land-evaluation units) delineated on large-scale maps based on climate, topography and soil characteristics including soil type, soil texture, stoniness and soil depth but not SOC content itself (Džatko 1981; Linkeš *et al.* 1996). A practical method how to acquire data on the SOC stock changes both in space and time for political decision-making is to employ process-based simulation models such as e.g. RothC (Smith *et al.* 2005, 2007; Milne *et al.* 2007; van Wesemael *et al.* 2010, etc.). RothC model was successfully applied also for the conditions of Slovakia. Data infrastructure was built up to run the model over the agricultural land of Slovakia and the validation of modelling results was done on several levels (Barančíková 2007; Barančíková *et al.* 2010a, b).

In this paper we present selected results of the RothC long-term simulation (1970–2007) of SOC stock changes in topsoils of arable land in Slovakia. Based on the results we will do statistical analyses of (*i*) the relationships between organic matter inputs to the soil and SOC stock changes in the conditions of Slovakia regarding socio-economic changes during the 1990's which significantly influenced the kind and amount of crop residues and farmyard manure input to the soil; and (*ii*) the relationships between simulated SOC stocks in topsoils and the soil production potential index, which is used for many political decisions possibly concerning also the negative changes in the SOC stock in agricultural soils of Slovakia.

MATERIAL AND METHODS

RothC model

Modelling of the SOC stock was based on RothC-26.3 model. RothC-26.3 (Colleman & Jenkinson 2005) was originally developed and parameterised to model the turnover of organic C in arable topsoils from the Rothamsted Long-Term Field Experiments.

The RothC-26.3 model requires three types of data:

(a) Climatic data – monthly rainfall (mm), monthly evapotranspiration (mm), average monthly mean air temperature (°C);

(b) Soil data – clay content (%), inert organic carbon (IOM), initial soil organic carbon (SOC) stock (t C/ha), depth of the soil layer considered (cm);

(c) Land use and land management data – soil cover, monthly input of plant residues (t C/ha), monthly input of farmyard manure (FYM) (t C/ha), residue quality factor (DPM/RPM ratio).

Further details of the RothC model and the model itself can be obtained from the paper of Barančíková (Barančíková *et al.* 2011) or from the GCTE SOMNET website.

Input data

The agricultural land of Slovakia was divided into regular spatial simulation units (SimU). Each SimU was designed so that it represented one cell of a 10 km resolution regular grid.

Point measurements (n = 70) of daily mean temperature (°C), potential evapotranspiration (mm), and rainfall (mm) were interpolated to the 10 km spatial resolution grid using an interpolation algorithm based on weather station similarity to unknown interpolated location (Groot 1998, Nováková 2007). The monthly rainfall (mm) and average monthly mean air temperature (°C) and evapotranspiration were calculated based on interpolated daily data.

Mean topsoil values of the initial SOC stock (t/ha) and clay content (%) in a 0–20 cm topsoil layer were calculated for each SimU using soil profile data coming from the national soil profile database (Skalský & Balkovič 2002). Soil profiles were stratified according to topsoil SOC content and topsoil texture prior to calculations. In this article the modelling of SOC changes on arable land is described.

NUTS4 (Nomenclature of Territorial Units for Statistics on a district level) level agricultural statistics on crop harvesting areas, crop yields and manure application rates were used as a source of soil management data. Regarding politically and socio-economically driven land use changes in Slovakia in the early 1990s, the land use data were interpreted separately for the periods 1970–1995 and 1996–2007. Crop harvesting areas were analysed to obtain regionally representative crop shares for the estimation of organic carbon inputs from crop residues. Published data (Jurčová & Bielek 1997) and default RothC model settings were used for the estimation of SimU-related monthly carbon inputs to soil (t/ha). FYM consumption statistics were a source for the analysis of regionally specific rates of manure application (t/ha). Published data (Jurčová & Bielek 1997) were used to estimate SimU-related monthly application rates of carbon manure (t/ha) separately for cropland and grassland.

More detailed information about delimitation of agricultural land and about input data can be found in the paper of Barančíková *et al.* (2011).

Basic statistical parameters between the SOC stock and organic carbon inputs/soil quality index were processed. The evaluation of statistical results was done in STATGRAPHIC Centurion.

RESULTS AND DISCUSSION

Long-term simulation in the period 1970–2007

The SOC stock modelling of cropland included 275 SimUs. The modelling period represented 37 years from 1970 to 2007.

According to the modelling data, the soil organic carbon stock on arable soils of Slovakia gradually increased, and the highest increase in the SOC stock was simulated in the first modelling period from 1970 to 1990. During this period the SOC stock increased about 16%. In the second modelling period 1990–2007 the increase in the total amount of SOC on all arable land of Slovakia was not so marked and was only 1.8% (Figure 1).

However, the increase in the organic carbon stock was not found out on all arable land. For this reason all arable land was divided according to development of the SOC stock during the modelling period. The grids in which the SOC stock gradually increased during the entire modelling period were in group A. This group included the highest number of SimUs and represented almost 60% of arable land of Slovakia. Group B included SimUs in which the SOC stock gradually increased until 1995 and then the stock of organic carbon remained more or less the same (Figure 2). This group represented 38% of arable land of Slovakia.

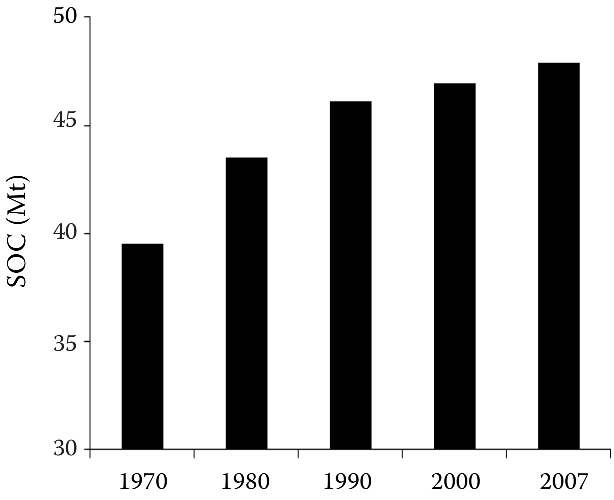

Figure 1. Modelling data on the total amount of soil organic carbon (SOC) during the modelling period in the whole territory of arable land of Slovakia

In the remaining modelling cells with the highest initial SOC stock modelling, SOC gradually decreased. This group was the smallest and represented only 2% of Slovak arable land (Figure 2).

Analysis of relationships between SOC stocks and organic inputs

RothC model takes into account soil parameters
– soil texture (clay content), climate parameters
– average monthly temperature, moisture and evapotranspiration and management parameters
– organic carbon inputs of plant residues and farmyard manures.

All these parameters influence the development of SOC stock, however, soil management is the most important and the first of all organic carbon input. Our data show a significant linear correlation between carbon input and the final simulated soil organic carbon stock for all arable soils (r = 0.4**, n = 275) and for soil groups A and B (Table 1); soil group C contained a small number of data for statistical processing. For this reason the main cause of different development of SOC on arable land can be different carbon inputs for the particular groups of SimUs.

As it can be seen from Table 1, the highest average organic carbon input for both modelling periods 1970–1994 and 1995–2007 was found out in group A with the smallest average initial SOC stock (Figure 2). In this group carbon input in the second modelling period was a little higher than in

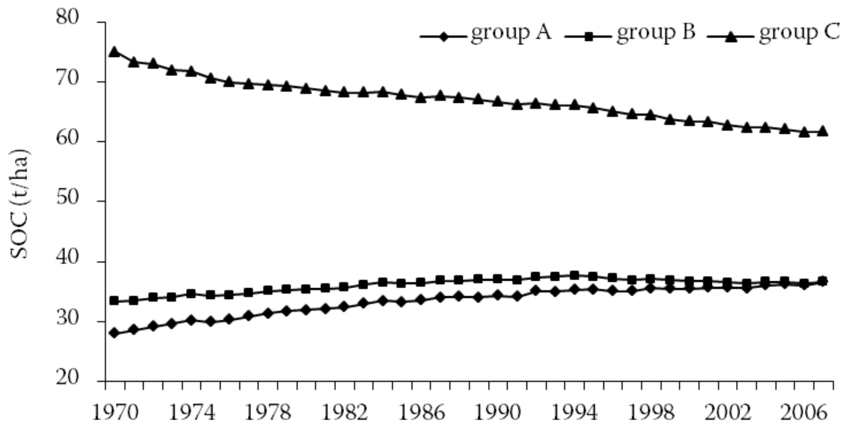

Figure 2. Development of soil organic carbon (SOC) stocks on Slovak arable land according to soil groups

the first modelling period. Therefore, in group A the organic carbon stock gradually increased (Figure 2). In group B the average initial carbon input was slightly higher in comparison with group A and the carbon input of modelling period was lower (Table 1).

In group B carbon input in the second modelling period was lower in comparison with the first modelling period (Table 1) and the SOC stock remained on the same level since the mid-90's (Figure 2). Both in group A and B the average initial carbon input was lower in comparison with carbon input during the modelling period (Table 1). A continual decrease of SOC stock during the modelling period on SimUs of group C with the highest initial carbon stock (Figure 2) was caused by lower carbon input during the modelling period in comparison with carbon input in the initial stage (Table 1).

The distribution of SOC stock on Slovak arable land is quite different and it reflects mostly the climate, topography and soil conditions of Slovakia (Figure 3).

Analysis of relationships between SOC stock and soil quality index

In Slovakia soil quality assessment is based on the assessment of landscape production potential (Džatko 1981). The landscape production potential reflects the ability of the landscape to produce a certain amount of crop yields. It is a processional characteristic of the landscape, which is represented on large-scale maps through the soil-ecological units whose boundaries are based on data on climate, topography and soil characteristics including soil type, soil texture, soil depth and stoniness but no information about SOC is included (Linkeš *et al.* 1996). The landscape production potential was analysed in Slovakia in the 1970s (Džatko 1981). Relations between crop yields and landscape-ecological units were investigated in representative localities for several selected crops (wheat, rye, barley, oats, maize, potatoes, sugar beet, perennial fodder crops); and the soil quality index values (SQV) were statistically estimated for each type of landscape-ecological unit ranging from 100 to 0 for the highest and the lowest productivity categories of landscape-ecological units, respectively.

The evaluation of SQV does not directly include organic carbon as a soil parameter and for this reason we tried to find out whether there was a relationship between SQV and SOC stock (Table 2).

Linear correlation coefficients between SQV and simulated SOC stock (2007) were statistically significant for all arable land as well as for group A

Table 1. Average values of carbon input in the first and second stage of modelling and linear correlation coefficients (r) between the final stock of soil organic carbon (SOC) and carbon input during the modelling period (in t/ha/year)

Grid's groups	C input			r
	initial	1970–1994	1995–2007	
A, n = 155	0.77	1.86	1.99	0.34**
B, n = 111	0.98	1.62	1.48	0.49**
C	1.71	1.68	1.61	

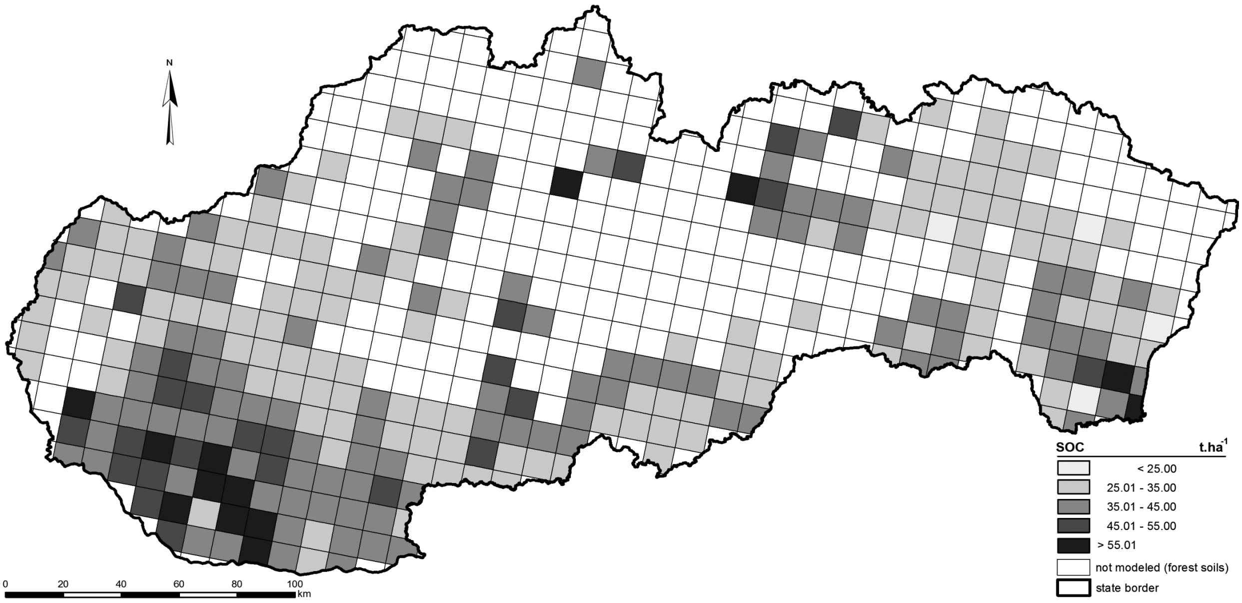

Figure 3. Map of final (2007) modelling data on the SOC stock on arable land of Slovakia

Table 2. Linear correlation coefficients between soil quality index values (SQV) and the final simulated soil organic carbon (SOC) stock (2007)

Grid's groups	Correlation coefficient
All arable land, n = 275	0.39**
A, n = 155	0.61**
B, n = 111	0.38**

and group B in spite of different developments of SOC stock during the modelling period (Table 2). Statistically significant correlations at the 95% confidence level were also determined between SQV and average organic carbon input (r = 0.56) and between SQV and change in the SOC stock in 2007 and 1970 (r = 0.37) on all arable land. The relationship between SQV and the modelled value of SOC stock can be explained by the fact that productivity SQV implicitly reflects those soil-landscape characteristics that are important for the SOC stock balance (climate conditions and soil conditions defined by soil texture and soil type).

On the basis of statistically significant correlation coefficients at the 95% confidence level we tried to find polynomial relationships (Table 3) to describe the relationship between the total SOC stock (2007 year) and productivity values.

Analysis of variance for the polynomial equation is in Table 4.

Since the P-value in Table 4 is lower than 0.05, the order of polynomial (order of polynomial = 2) is statistically significant at the 95% confidence level.

Table 3. A polynomial model for the relationship between the soil organic carbon stock and soil quality index values in arable land

Arable land	Polynomial eqauation
	final SOC stock (2007 year) = 75.5936 – 1.6333 × SQV + 0.015245 × SQV^2

Table 4. Analysis of variance for the polynomial equation (relationship between soil organic carbon stock and soil quality index values in arable land)

	Source	Sum of squares	Mean square	F-ratio	P-value
All arable land	model	7796.21	3898.1	84.42	0.0000
	residual	12375.3	46.1767		
	total (corr.)	20171.6			

Environmental and political implications

The long-term RothC simulations of carbon stocks in the topsoil of cropland soils of Slovakia show in general an increase in the SOC stocks over the entire simulation period 1970–2007. From a more detailed analysis of the results, some temporal differences in the dynamics of SOC stock changes were observed.

Results proved our anticipation that the amount and the kind of organic residues coming to the soil influence the observed temporal variability of simulated topsoil SOC stocks significantly along with natural conditions (climate and soil properties). The amount of crop residues and farmyard manure coming to the soil both in the first and second simulation period (1970–1995 and 1996–2007) was responsible for general trends in the SOC stock dynamics which corresponded well with the results of Schulp and Verburg (2009) and van Wesemael *et al.* (2010).

It can be concluded from the obtained results that the balanced or positive SOC stock dynamics is one of the primary conditions of sustainable use of soils in Slovakia. For this reason changes in the SOC stock could be influenced positively or negatively by political measures set for the agricultural sector on the EU or national level.

We have also found out that the value of the soil production potential index generally used for soil quality assessment in Slovakia corresponds well with simulated values of SOC stocks in topsoils of cropland soils. It means that regardless of the origin and kind of soil production potential index, it reflects well the soil and landscape processes responsible for SOC dynamics in the soil; and as such, it can be used in Slovakia as the soil quality information input for decision-making which concerns the SOC stock management in agricultural soils.

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References

Andrews S.S., Karlen D.L., Cambardella C.A. (2004): The soil management assessment framework. Soil Science Society of America Journal, **68**: 1945–1962.

Barančíková G. (2007): Validation of RothC model on selected monitoring localities**.** Vedecké práce VUPOP, **29**: 9–22 (in Slovak).

Barančíková G., Šoltýsová B., Koco Š. (2010a): Prediction of soil organic carbon stock in conditions of Eastrer Slovak Lowland. Agriculture, **56**: 35–45.

Barančíková G., Halás J., Gutteková M., Makovníková J., Nováková M., Skalský R., Tarasovičová Z. (2010b): Application of RothC model to predict soil organic carbon stock on agricultural soils of Slovakia. Soil and Water Research, **5**: 1–9.

Barančíková G., Gutteková M., Halas J., Koco Š., Makovníková J., Nováková M., Skalský R., Tarasovičová Z., Vilček J. (2011): Soil Organic Carbon in Agricultural Land – Modelling of Changes in Space and Time. VÚPOP, Bratislava, 12–17, 47–58 (in Slovak).

Coleman K., Jenkinson D.S. (2005): ROTHC-26.3 A model for the turnover of carbon in soil. Model description and windows users guide. Available at http://www.rothamsted.bbsrc.ac.uk/aen/carbon/mod26_3_win.pdf

Džatko M. (1981): Principles of synthetic – parametric method for evaluation of soils of Slovakia. Rostlinná výroba, **27**: 451–459 (in Slovak).

EC (2006a): Proposal for a Directive of the European parliament and of the council establishing a framework for the protection of soil and amending Directive 2004/35/EC, Brussels.

EC (2006b): Communication of 22 September 2006 from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions: Thematic Strategy for Soil Protection. Europa Press Releases RAPID, Brussels.

Eckelmann W., Baritz R., Bialousz S., Bielek P., Carré F., Houková B., Jones R.J.A., Kibblewhite M., Kozak J., Le Bas C., Tóth G., Tóth T., Várallyay G., Halla M.Y., Zupan M. (2006): Common Criteria for Risk Area Identification according to Soil Threats. European Soil Bureau Research Report No. 20, EUR 22185 EN. Office for Official Publications of the European Communities, Luxembourg.

Groot E. van der (1998): Spatial interpolation of daily meteorological data for the Crop Growth Monitoring System (CGMS). In: Bindi M., Gozzini B. (eds): Proc. Seminar on Data Spatial Distribution in Meteorology and Climatology. September 28–October 3, 1997, Volterra, The Office for Official Publications of European Communities, Luxembourg, 141–153.

Jurčová O., Bielek P. (1997): Sorces, losses and balance of soil organic matter. In: Gonet S., Zaujec A. (eds): Humic Substances in Environment 1, Polish Humic Substances Society, Bydgoszcz, 9–12.

Linkeš V., Pestún V., Džatko M. (1996): Guidelines for Using Maps of Land-Evaluation Units. VÚPÚ, Bratislava. (in Slovak)

Milne E., Al Adamat R., Batjes N.H., Bernoux M., Bhattacharyya T., Cerri C.C., Cerri C.E.P., Coleman K., Easter M., Fallon P., Feller C., Gicheru P., Kamoni P., Kilian K., Pal D.K., Paustian K., Powlson D.S., Rawajfih Z., Sessay M., Williams S. (2007): National and sub-national assesments of soil organic carbon stocks and changes: The GEFSOC modeling system. Egriculture, Ecosystems & Environment, **122**: 3–12.

Nováková M. (2007): Weather interpolation as a baseline for crop growth monitoring and crop yield forecasting. Vedecké práce VÚPOP, **29**: 95–105. (in Slovak)

Ogle M.S., Paustian K. (2005): Soil organic carbon as an indicator of environmental quality at the national scale: Inventory monitoring methods and policy relevance. Canadian Journal of Soil Science, **85**: 531–540.

Schulp C.J.E., Verbung P.H. (2009): Effect of land use history and site factors on spatial variation of soil organic carbon across a physiographic region. Agriculture, Ecosystems and Environment, **133**: 86–97.

Skalský R., Balkovič J. (2002): Digital Database of Selected Soil Profiles of Complex Soil Survey of Slovakia (KPP-DB). Proceedings VÚPOP, **25**: 129–139.

Smith J., Smith P., Wattenbach M., Zaehle S., Hiederer R., Jones R.J.A., Montanarella L., Rounsevell M., Reginster I., Ewert F. (2005): Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080. Global Change Biology, **11**: 2141–2152.

Smith J., Smith P., Wattenbach M., Gottschalk P., Romanenkov V.A., Ševcova L.K., Sirotenko O.D., Rukhovič D.I., Koroleva P.V., Romanenko I.A., Lisovoj N.V.(2007): Projected changes in the organic carbon stocks of cropland mineral soils of European Russia and the Ukraine 1990–2070. Global Change Biology, **3**: 342–356.

Stolbovoy V., Montanarella L. (2008): Application of Soil organic carbon status indicators for policy-decision making in the EU. In: Toth G., Montanarella L., Rusco E (eds): Threats to Soil Quality in Europe. JRC Scientific and Technical Reports, Ispra.

Stolbovoy V., Montanarella L., Filippi N., Jones A., Gallego J., Grassi G. (2007): Soil sampling protocol to certify the changes of organic carbon stock in mineral soil of the European Union. Version 2, EUR 21576 EN/2, Luxembourg.

van Wesemael B., Paustian K., Meersmans J., Goidts E., Barančíková G., Easter M (2010): Agricultural management explains historic changes in regional soil carbon stocks. PNAS, **107**: 14926–14930.

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