Short communication

SOIL COMPACTION AND SUSCEPTIBILITY TO COMPACTION IN THE AGRICULTURALLY USED SOILS

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Abstract
Soil compaction belongs to the main threats to soils decreasing their fertility and destabilizing soil functions and relationships with the other components of environment. Soil compaction can be divided into three main categories: primary or natural coming out from soil properties, secondary or induced by man due to improper soil use and combined based on the first two categories. Soil susceptibility to compaction is not uniform and depends on soil properties from which the main are soil texture and soil type which determines the arrangement and kind of horizons in soil profile. Map showing soil susceptibility to compaction was created on country and European levels. Such maps can help users to determine the type of soil use to prevent soil degradation, to prevent soil compaction.
Keywords: soil compaction, soil susceptibility to compaction, soil maps, soil properties, soil typological units and susceptibility to compaction

INTRODUCTION

Soil compaction belongs to the main threats facing agricultural soils and can be seen as a trigger and accelerator of other threats, mainly soil erosion (Jones, Houšková *et al.* 2005). Definition of soil compaction introduces this threat as the rearrangement of soil aggregates and/or particles in a denser way when the voids and pores mainly between the aggregates and particles become smaller or are even missing in comparison with the arrangement of similar but not compacted soil. The lateral orientation, size and shape of soil aggregates are evidence of soil compaction. Arrangement of the aggregates is with the longer side in a horizontal way (platy structure), they do not have a round and, depending on the intensity of compaction, they can be destroyed if the compaction is too severe.

Resistance of soils to compaction is not uniform and determines the soil susceptibility to compaction. Such susceptibility is the probability that soil becomes compacted when exposed to compaction risk. It can be low, medium, high, and very high depending on soil properties, mainly texture and type of soil horizons, and a set of external factors like climate, type of soil use, influence of the other threats, etc. There can be different reasons for soil compaction and soil susceptibility; thus, they are divided into two main groups: *natural* – primary and *man-induced* – secondary as well as one subgroup: *combined,* which is the result of the two previous occurring simultaneously at the same place, *in situ*.

Reasons for natural soil susceptibility to compaction

The reasons for natural soil susceptibility to compaction are resulting from the soil properties and the typical climate of the evaluated area (Häkansson 2005). The soil properties mainly involved in soil susceptibility to compaction are soil texture, arrangement and type of soil horizons, pH, humus or organic matter content, amount of salts in soil water and soil matrix, ground water presence and type of water regime. More or less all these properties are reflected in the soil type. Natural soil susceptibility to compaction can thus be evaluated according to texture, structure, porosity, bulk density, and soil type.

Soil texture and physical properties

Soil texture

Soil susceptibility to compaction is influenced predominantly by its texture, mainly by the clay fraction (size <0.002 mm). The higher the clay fraction content, the more susceptible is the soil to compaction. Soil texture influences consecutively the other soil properties, e.g., porosity, size, and type of soil aggregates. Increase of soil susceptibility to compaction goes in the direction: sandy – loamy sandy – sand loamy – loamy – clay loamy – loam clayey – clayey soils – clays (Tab. 1). Clays are the most susceptible to natural compaction (Rode 1956, Woods *et al.* 1944) because of the weight of the soil; clay soils are the heaviest soils. In the case of heavy soils, the upper parts of the soil compact the lower parts due to their weight. They have high water holding capacity because of high content of clay minerals with large surface and inter-layers, which are able to attract water. On the other hand, such soils have a short time of suitable water content in their profile for cultivation. Such type of soils is called "*minute soils*".

Table 1

Evaluation of soil susceptibility to compaction according to soil texture

Textural codes in land evaluation units (LEUs) (Linkeš, Pestún, Džatko 1996)	Description	Evaluation
1	Sandy and loamy-sandy soils	L
2	Clay soils	M/H*
3	Clay-loamy soils	M/H*
4	Clayey soils and clays	VH
5	Sandy-loamy	L/M*

Explanations: * – final evaluation can be influenced by amount of organic matter and/or sand
L – low, M – medium, H – high, VH – very high susceptibility

Texture plays a key role in soil susceptibility to compaction because it influences directly ground-bearing capacity. Texture has also indirect influence through the determination of total organic matter content according to a generally valid rule stating that with the increase of clay content also organic matter content increases.

Soil structure

The soil aggregates stability, their shape and size – soil structure, are evidence of soil texture type and status of soil from compaction point of view. Kutílek (1978) describes approximate assessment of the structural state of humus horizon according to bulk density for medium to heavy soils (Tab. 2). Lower values of bulk density apply to heavy soils.

Table 2

Approximate assessment of the structural state of humus horizon according to bulk density (according to Kutílek 1978)

Structure of humus horizon	Bulk density of humus horizon (g.cm^{-3})
Good	1.2
Satisfactory	1.2–1.4
Unsatisfactory	1.4–1.6
Unstructured soil	1.6–1.8

Light soils are the most resistant to soil compaction and they can tolerate much higher bulk density values, even 1.6–1.7 g.cm^{-3} are tolerable for them. Soil bulk density serves as one of the main indicators of soil compaction (Häkansson 2005, Houšková 2002, Tóth, Montanarella, Rusco 2008) and one of the basic directly measured soil input parameters used in computer models related to the movement of water in the soil as well as other soil regimes (Bruand, Blaize, Hardy 1994, Bruand *et al.* 1996).

Soil porosity (P)

It is the part of a certain volume of soil not filled with a solid phase – soil mass and contains air, water, or both (Kutílek 1978). Pores are mostly continuous and vary in shape and size. According to the size, the pores are divided into capillary, non-capillary and semi-capillary. Their sum is equal to the total porosity. Capillary pores have a size from 0.003 to 0.05 mm (Slovík & Libant 1997) and water can also move in them against the direction of the earth's gravity. Van der Waals attractive forces apply here. The lift of water in the capillary is given by the equation:

$$h = 0.3\frac{1}{d}$$

d – capillary diameter

Non-capillary pores are larger than 0.5 mm and water moves in them exclusively in the direction of gravity. Semi-capillary pores are transitional pores between capillary and non-capillary. Soil porosity is also used in the assessment of soil compaction. In general, it is customary to assess the total soil porosity, which can give a distorted view of the given issue, as during the compaction process the total porosity does not have to change, but the representation of pores changes in favour of capillary ones. Soil porosity is also used as an input to computer programs and models.

The approximate classification of soil density according to porosity is as follows (Kutílek 1978) (Tab. 3).

Table 3

Soil porosity and density (Kutílek 1978)

Porosity of light soils (% vol.)	Mark of soil density	Porosity of medium heavy and heavy soils (% vol.)
	Plough layer	
>65	loose	> 65
65–50	slightly dense	65–55
50–40	dense	55–45
<40	very dense	<45
	Subsoil	
>50	loose	>57
50–43	slightly dense	57–46
43–35	dense	46–35
<35	very dense	<35

Bulk density (rd)

Bulk density is the mass of soil (m_z) under the natural arrangement of soil particles related to the volume (Vs) of this soil (Kutílek 1978):

$$d = \frac{m_z}{Vs}$$

The above formula represents the calculation of the so-called reduced bulk density, i.e., weight of dried soil. This value depends on the mass of the solid phase of the soil (m_z) and on the porosity (P). The bulk density value varies from 0.2 $g.cm^{-3}$ for peat to 1.8 $g.cm^{-3}$ for strongly compacted and sandy soils. It changes during the year and is strongly dependent on soil moisture, while it is true that the change in volumetric weight is the largest in the upper horizons.

Soil water regime and ground water presence

The soil water regime influences its susceptibility to compaction and is vice-versa influenced by compaction. The soil water regime summarizes the movement of water through the soil profile in time and space (Houšková 2008). The direction of the water movement in the soil is defined by the soil moisture potential. The processes involved in water redistribution are infiltration, soil evaporation, transpiration by plants, water redistribution, capillary rise of water from the ground water table and percolation of water through the unsaturated zone to ground water table, internal drainage and sub-surface run-off. All of these processes (if present) may happen at the same time. According to the type of water regime, the proportion of precipitation (P) and evapotranspiration (PET) determines soil susceptibility to compaction.

Five main situations can occur according to Rode (1956)

1. Water regime of soils with permafrost.
2. Percolative and periodically percolated water regime (P/PET>1 and P = PET respectively, where P is percolation and PET is potential evapotranspiration). In case of percolated water regime, the evapotranspiration from soils is lower than infiltration during a major part of the year. The movement of water in the soil profile is mostly descending. In case of periodically percolated water regime, periods with evapotranspiration, higher than infiltration, alternate with periods of lower evapotranspiration and higher infiltration.
3. In percolated water regime (P/PET<1). The evapotranspiration exceeds percolation during most of the year. The lower parts of the profile have lack of water during all the year and are close to wilting point.
4. Evaporative water regime (P/PET<1). Movement of water through soil profile is mostly ascending. Ground water supply is present.
5. Irrigation water regime ((P + Z)/PET = 1, in case of over irrigation (P+Z)/PET>1). Z is water supply from irrigation.

In cases 1 and 2, soils are susceptible to compaction. Case 5 can create man-induced type of soil compaction.

The ground water table (Häkansson 2005) plays an important role in soil susceptibility to compaction. In the soil environment two main situations may occur:

1. The ground water level is situated deep and thus is not involved into the water balance of a soil profile, which means finally that soil susceptibility to compaction because of ground water presence is low.
2. The ground water level is in hydraulic contact with the soil profile and is involved into its water balance. This is characteristic for all hydromorphic soils like Fluvisols, Gleysols and Histosols (Working Group WRB 1998, IUSS Working group WRB 2015).

In addition, soil susceptibility to compaction may vary from medium to high or very high in dependence on how deep the ground water level is. The closer to the soil surface, the higher the susceptibility to compaction.

Chemical properties

The most important chemical soil properties in relation to compaction is the excess of salts in the soil profile, which decreases the stability of the soil structure. pH is also an important factor. A low pH is unfavorable for soil aggregates stability, thus soils with low pH are more susceptible to compaction.

Biological properties

Biological soil properties are rather the result of soil compaction than the reason for soil compaction. Soil biota, both micro and macro-organisms are influenced by the change of soil properties due to compaction. Soil properties with high influence on soil biota, are temperature, water and air regime, amount and redistribution of available nutrients (their occurrence in compacted soils is mainly in upper parts of topsoil, the rest of soil profile is without nutrients, water and air), pH and Eh (redox potential), soil density (this influences redistribution of e.g., earthworms). High humus or organic matter content can increase soil susceptibility to compaction in case of medium heavy or heavy soils; however, light sandy soils are an exception from this rule. In general, even if sandy soils have a low humus or organic matter content, they have also low susceptibility to compaction.

Arrangement and kind of soil horizons – soil typological units

Accumulation of clay in a so called "*argic horizon*" is a driving force for the formation of compaction features in the soil (IUSS Working Group 2015). Such horizon has a low or significantly decreased water permeability, which leads to water stagnation above this horizon with subsequent destruction of the soil structure. High water content and unstable structure create *compaction conditions.* The accumulation of salts is connected with the low stability of soil aggregates (as mentioned above). Leaching processes, like podsolization and illimerisation, and clay movement decrease the soil structure stability and influence water movement in soil profile.

A more detailed evaluation of soil susceptibility to compaction is related to the second level units of soil classification system, for instance the use of qualifiers in the WRB. Qualifiers serve a more detailed evaluation of soils and many of them are typically associated to the reference group. In the WRB, there are prefix principal qualifiers and suffix supplementary qualifiers. Especially qualifiers related to chemical, physical, mineralogical, and textural characteristics can significantly influence the evaluation of soil susceptibility to compaction of reference soil groups. Qualifiers can change the final definition of soil susceptibility of soil types in the reference soil group.

For the evaluation of soil susceptibility to compaction, the reference soil groups in combination with second level units always takes precedence over just the single reference soil group (Working Group WRB 1998) (Tab. 4).

Table 4

Evaluation of susceptibility to compaction on the level of main reference soil groups typical for Slovakia

WRB (1998) RSG codes and their meaning / susceptibility to compaction					
AB	Albeluvisol	**H**	LP	Leptosol	**L**
AN	Andosol	**L**	LV	Luvisol	**H**
AT	Anthrosol	**NE**	PH	Phaeozem	**L**
AR	Arenosol	**L**	PL	Planosol	**H**
CM	Cambisol	**M**	PZ	Podzol	**M**
CH	Chernozem	**L**	RG	Regosol	**L**
FL	Fluvisol	**M**	SC	Solonchak	**H**
GL	Gleysol	**H**	SN	Solonetz	**H**
HS	Histosol	**L**	VR	Vertisol	**H**

Explanations: L – low, M – medium, H – high, VH – very high susceptibility, NE – not evaluated

The main principles of the evaluation of soil susceptibility to compaction according to soil units are resulting from the properties specific for the unit and profile forming horizons (Working Group WRB 1998) (Tab. 5).

Table 5

Evaluation of the susceptibility to compaction on the level of soil subunits (WRB_ADJ)

WRB (1998) adj codes and their meaning / susceptibility to compaction								
ao	Acroxic	**L**	rz	Rendzic	**L**	rs	Rustic	**H**
ab	Albic	**M**	fr	Ferric	**H**	sz	Salic	**H**
an	Andic	**L**	fi	Fibric	**L**	sa	Sapric	**L**
ar	Arenic	**L**	ge	Gelic	**H**	so	Sodic	**H**
ad	Aridic	**NR**	gl	Gleyic	**H**	st	Stagnic	**H**
ca	Calcaric	**L**	gs	Glossic	**L**	ti	Thionic	**M**

Explanations: *LOW – in case of diffuse form of secondary carbonates; *HIGH – in case of cutans and nodules; L – low, M – medium, H – high, VH – very high susceptibility, NR – not relevant, NE – not evaluated

WRB (1998) adj codes and their meaning / susceptibility to compaction								
cc	Calcic	**L/H***	ha	Haplic	**NR**	tu	Turbic	**M**
cb	Carbic	**H**	hi	Histic	**L**	um	Umbric	**L**
ch	Chernic	**L**	hu	Humic	**L**	vr	Vertic	**H**
cr	Chromic	**NR**	le	Leptic	**NR**	1	Town	**NE**
cy	Cryic	**H**	li	Lithic	**NR**	2	Soil disturbed by man	**NE**
dy	Dystric	**M**	Iv	Luvic	**H**	3	Water body	**NR**
et	Entic	**H**	mo	Mollic	**L**	4	Marsh	**NR**
eu	Eutric	**L**	pe	Pellic	**NR**	5	Glacier	**NR**
pr	Protic	**L**	pi	Placic	**H**	6	Rock outcrops	**NR**

Explanations: *LOW – in case of diffuse form of secondary carbonates; *HIGH – in case of cutans and nodules; L – low, M – medium, H – high, VH – very high susceptibility, NR – not relevant, NE – not evaluated

In principle, the presence of a horizon with high susceptibility to compaction increases inclination of soil to compaction even if according to the main group the susceptibility is low, e.g., Luvic Chernozem. On the contrary, high susceptibility of soil to compaction according to the main group decreases if in the profile a horizon with low susceptibility is present, e.g., Mollic Gleysol.

Generally, applicable rule is that the natural origin of soil compaction leads very often to compaction in the whole profile or its deeper parts.

Reasons for man induced and combined susceptibility to soil compaction

Man-induced or *secondary* soil susceptibility to compaction is created in the case where possible soil compaction is not the desired result of human activities but as the result of improper soil utilization, especially in agricultural and forest practices. Man induced soil compaction affects soils that are naturally not susceptible to compaction and/or significantly increases the natural susceptibility. The latter is denoted as the *combined type* of soil susceptibility to compaction. Type and extent of soil use can create secondary soil susceptibility to compaction. In the case of agricultural soils, the creating of narrow ditches and soil ploughing, especially to the same depth, can create soil compaction. The other reasons include intensive or incorrect land use (agriculture, forest management), low amount of deep rooting structure forming plants in crop rotation, e.g., fodder crops, high amount of root crops (plants risky for soil properties stability: root system, cultivation practices with high amount of crossing on the field), low amount of organic residues.

In all these cases, the soil balance with the surrounding environment is broken and usually there is not enough time to come into the natural balance again. The renewed or new balance is less stable than the natural one and soil susceptibility to compaction can then be higher than in case of natural soil belonging to the same textural category and having the same type of soil horizons and their configuration.

Treatment of soils in building areas leads to significant changes of the natural properties of soil; very often-such changes leading to soil compaction are done on purpose and compaction is the aim of such works. In this case, soils lose their natural functions.

A basic rule (for good agricultural practices) when estimating the proper time for soil cultivation e.g., ploughing is that soil moisture content during ploughing has to be around 0.9 of the field capacity (Lhotský *et al.* 1984). Especially in the case of heavy soils, which might be wetted at the beginning of the cultivation period, due to lower hydraulic conductivity, this moisture interval does not always occur, and compaction can arise.

In the Tab. 6 is general soil moisture according to the textural categories (acc. to Šútor *et al.* 1995) and proper soil moisture for cultivation. Upper and subsoil horizons are the most important. Depending on the depth of cultivation (e.g., ploughing) also the critical soil layer depth varies.

Table 6

General soil moisture according to the textural category and proper soil moisture for cultivation; both in percentage of volume (Šútor *et al.* 1995)

Soil textural category	Soil horizon (m)	θ_s	θ_{fc}	Proper soil moisture for cultivation (0.9 Qfc)
		(% of volume)		
Light soils	0–0.30	43.93	28.11	25.30
	0.31–0.80	44.26	27.71	24.94
	0.81–1.10	42.95	28.02	25.22
Medium heavy soils	0–0.30	45.35	34.09	30.68
	0.31–0.80	41.98	33.74	30.37
	0.81–1.10	40.47	33.25	29.93
Heavy soils	0–0.30	45.99	37.52	33.77
	0.31–0.80	43.83	36.91	33.22
	0.81–1.10	42.13	36.52	32.87
Very heavy soils	0–0.30	49.23	40.15	36.14
	0.31–0.80	45.15	40.9	36.81
	0.81–1.10	45.51	40.09	36.08
Clay	0–0.30	50.17	43.5	39.15
	0.31–0.80	50.06	45.44	40.90
	0.81–1.10	50.54	47.87	43.08

*Explanations: Q_s – full saturation of soil profile by water; θ_{fc} – moisture content at field capacity

Agricultural machinery in conventional type of soil cultivation has many passes through the field. This influences about 50% of the field area. The amount of passes depends on the type of cultivated plant and for instance, the number of passes needed for root crops cultivation is 225% of field area; this means that a field with root crops is exhibited to passes more than 2 times.

The balance of such soil is very fragile because of the high amount of possible soil degradation agents; especially in case of heavy soil with very low moisture interval suitable for cultivation. In case of clayey soils, this interval is very short, and it is very difficult for farmers to be in accordance with soil moisture during cultivation.

Ploughing of soil to the same depth for several years accelerates plough-pan genesis even if done in proper soil moisture content.

For human induced soil compaction, the compacted layer in the depth of 0.1–0.25 m (plough pan) is typical. Deeper soil compaction is typical for naturally induced processes (Table 7).

Table 7

Predicted crop yield losses and increased tillage costs due to soil compaction on the plough layer and in the subsoil (Häkansson 2005)

Type of effect	Non-aggressive spreading			Aggressive spreading		
	10%	**30%**	**50%**	**10%**	**30%**	**50%**
1.Effects in the plough layer in the same year (%)[a]	2.8	2.8	2.8	8.9	8.9	8.9
2. Residual effect in the plough layer (%)[b]	0.2	0.6	1.0	1.5	4.6	7.7
3. Effects in the 25–40 cm layer (%)[c]	0.1	0.1	0.1	0.9	0.9	0.9
4. Effects in the >40 cm layer (%)[d]	–	–	–	0.3	0.3	0.3
Total yield loss (%, sum of 1–4)	**3.1**	**3.5**	**3.9**	**11.6**	**14.7**	**17.8**

Type of effect	Non-aggressive spreading			Aggressive spreading		
	10%	**30%**	**50%**	**10%**	**30%**	**50%**
Total yield loss (€ ha^{-1}):						
at an annual crop value of 500 € ha^{-1}	15	17	19	58	73	89
at an annual crop value of 1 000 € ha^{-1}	31	35	39	116	147	178
Increased tillage costs (€ ha^{-1})^{e}	2	4	6	5	9	13
Total loss (yield loss + increased tillage costs, (€ ha^{-1}):						
at an annual crop value of 500 € ha^{-1}	17	21	25	63	82	102
at an annual crop value of 1 000 € ha^{-1}	33	39	45	121	156	191

Material and methods for creation of soil maps considering their susceptibility to compaction

Method used for map construction is based on the creation of logical connections between chosen parameters having importance in the process of evaluation of soil susceptibility to compaction. These logical connections – *pedotransfer rules* – have been created by use of the parameters taken from the LEU database and expert knowledge.

Soil susceptibility to compaction can be evaluated according to the two main principles and their combination – principle 3:

Principle 1 results from natural soil properties and their combination resulting in different extents of soil susceptibility to compaction.

Principle 2 is based on human induced susceptibility of soil to compaction based on different types of soil use.

Principle 3 is the combined susceptibility of soil to compaction. i.e. natural and man-made susceptibility on the same physical soil area.

LEU code (Linkeš, Pestún, Džatko 1996) is the combination of 7 digit-code representing climate, main typological unit, slope, stoniness, exposition, soil depth, and texture (Fig. 1).

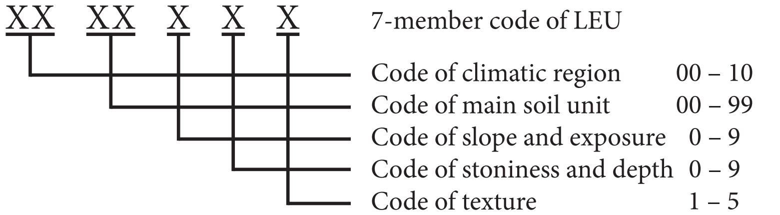

Figure 1 Structure of the LEU code

For the purposes of map construction the code for main soil unit and texture of topsoil was used with textural categories divided according to Novak´s textural fraction <0.01 mm as follows: sandy soils (0–10% of <0.01 mm), loamy-sandy soils (10–20%), sandy-loamy (20–30%), loamy (30–45%), clay-loamy (45–60%), clayey (60–75%), and clay (>75%).

After selection of suitable parameters (codes) for soil susceptibility to compaction was determined by evaluation of selected parameters and pedotransfer rules have been created. Final output of soil susceptibility results from information coming from combination of both selected parameters – soil typological units (subunits) and soil texture.

Establishment of pedotransfer rules

Pedotransfer rules have been created for the evaluation of the natural soil susceptibility from the basic assumption:

If the soil represents a given soil unit (WRB_GRP) with a given soil subunit (WRB_AD or national classification) and has a specific topsoil and subsoil texture (TEXT_SRF), THEN the soil has low, medium, high, or very high natural susceptibility to compaction in dependence of the assessed parameters.

Selected parameters of the ESDAC (European Soil Data Centre) have been evaluated according to this basic premise and natural soil susceptibility to compaction was set up for the purpose of map construction (Houšková & Montanarella 2008). The greatest simplification was in two marginal situations:

1. if both selected parameters show high susceptibility to compaction, then the soil has a very high final susceptibility to compaction;
2. if both selected parameters show low susceptibility to compaction, then the soil has a low final susceptibility to compaction.

For the case 1, in the final evaluation, parameters with high susceptibility have been evaluated with higher value as it was in the case 2 in which there are parameters with low susceptibility. The reason for this is the assumption that if soil has all the properties relevant for susceptibility to compaction in bad status (high susceptibility), its final susceptibility is very high. On the contrary, if soil has all relevant properties in good status (low susceptibility), this will not influence final susceptibility, which is already low, because every soil as porous medium has some susceptibility to compaction, so always the susceptibility is present.

The rest of cases have been evaluated according to the *basic assumption* and expert knowledge. Direct mathematical operations or pure combinatory analysis are not enough for a given evaluation because soil is too complex part of the environment.

RESULTS AND DISCUSSION

An actualized version of the Map of Natural Susceptibility of Soils to Compaction was elaborated from evaluation of the selected parameters comprised in Land Evaluation Units (LEU), the database owned and copyright by Soil Science and Conservation Research Institute Bratislava.

The map is created in ArcGIS program, version 9.3, using ArcMap and is stored as a shape file with attributes table. The Attribute table contains attributes of evaluation. FID, Shape, BPEJ (LEU), Kod_KU, Shape_AR_1, F_ Area and Susceptibility_Compaction.

According to this map soils are divided into 4 categories:

1. Low susceptibility to compaction
2. Medium susceptibility to compaction
3. High susceptibility to compaction
4. Very high susceptibility to compaction

Such a division can help farmers, soil owners and the other soil users to decide the type of soil utilization according to its susceptibility to compaction and can contribute to the prevention of soil degradation coming from improper cultivation and crop rotation. Generally, it is not recommended to use very heavy and heavy soils for root crops cultivation and crops demanding high water supply not to cultivate on light soils with low water holding capacity.

Soils with naturally low susceptibility to compaction

The group is characterized by soil units Andosol, Arenosol, Chernozem, Histosol, Leptosol, Phaeozem, and Regosol (Working group WRB 1998). In case that these soils have no argic horizons or the features of water stagnation in their profiles, e.g., Luvic qualifier and are not used very intensively, their susceptibility to compaction is low. In case of very fertile soils, secondary susceptibility induced by intensive use has been taken into account and such soils have final susceptibility marked as medium. These soil units and subunits have predominantly coarse texture and belong to the so-called light soils. They easily become dry.

Soils with naturally medium (M) susceptibility to compaction

Soil units and subunits having medium susceptibility to compaction are Cambisols, intensively used Chernozems, Fluvisols, Podzols and medium heavy and intensively used Phaeozems (Working group WRB 1998). These soil units and subunits have predominantly medium and medium fine texture and belong to the medium heavy soils.

Soils with naturally high (H) susceptibility to compaction

Soil units and subunits having high susceptibility to compaction are Albeluvisols, Gleysols, Solonchak, Solonetz and all fine textural categories especially in case of intensively used soils like heavy Chernozems, heavy Phaeozems, etc. (Working group WRB 1998).

As coming out from soil typological units these soils beside fine texture have also another limitation, mainly excess of salts. They belong to so called heavy soils.

Soils with naturally very high (VH) susceptibility to compaction

These soils in general have several limitations. The main limitation is excess of salts, shallow water table, or a combination of both. They might be flooded and stagnation of water after heavy rains is typical for their surfaces. Combination of salts excess with very fine texture is driving force for their high susceptibility to compaction. As in general, their very fine texture limits fertility, the man-induced susceptibility to compaction is usually not the crucial factor influencing it. On the other hand, it must be stated, that these soils are very sensitive to improper cultivation connected with the use of heavy machinery and frequent traffic on their surfaces. They belong to very heavy soils.

Map showing the natural susceptibility of agricultural soils of Slovakia to compaction if they were to be exposed to real compaction, based on the creation of logical connections between relevant parameters as soil type and texture using pedotransfer rules was compiled for the agricultural soils of Slovakia (Fig. 2).

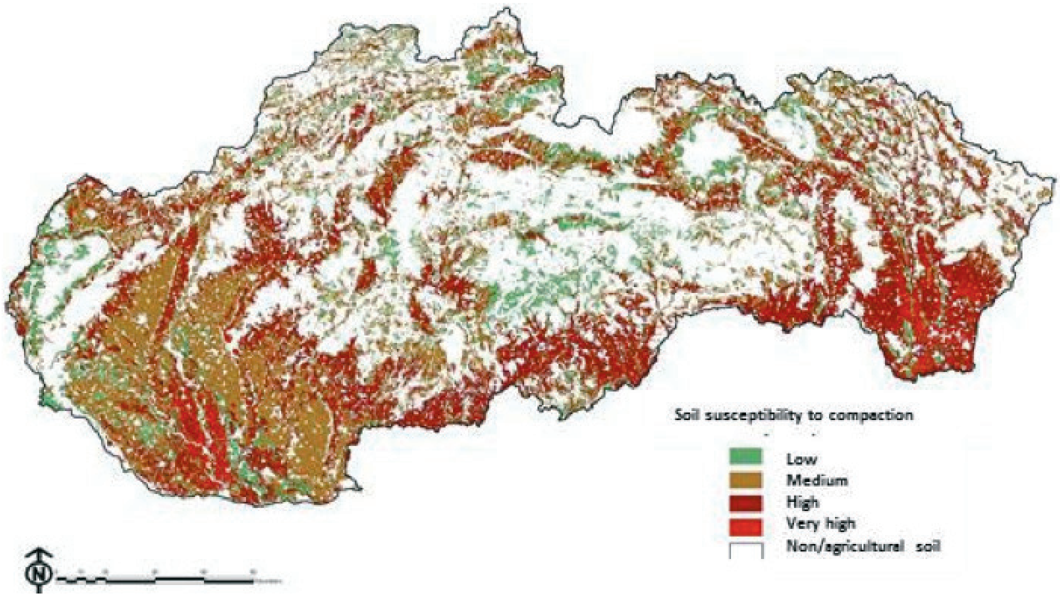

Figure 2 Map of soil susceptibility to compaction in Slovakia

Similarly the map of soil susceptibility to compaction was created also at European level (European Soil Data Centre, Houšková 2008) using pedotransfer rules with input parameters taken from the attributes of the European soil database, assessing soil properties as soil type, texture and water regime, depth to textural change and the limitation of the soil for agricultural use (Fig. 3). Besides the main parameters, auxiliary parameters have been used as impermeable layer, depth of an obstacle to roots, water management system, dominant and secondary land use. It was assumed that every soil, as a porous medium, could be compacted.

Short communication

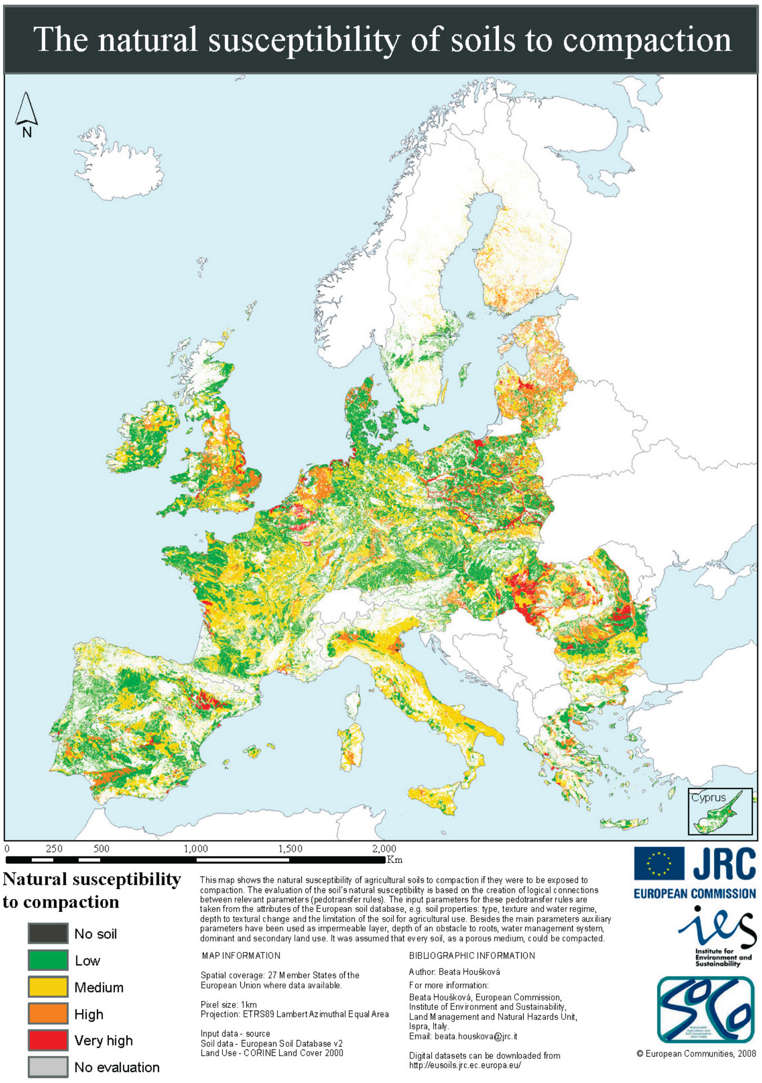

Figure 3 Map of soil susceptibility to compaction in Europe

How to cultivate soils to prevent soil compaction

Good agricultural practices using soil saving technologies as minimum till, no till, mulch application can contribute to soil biodiversity increase which is at present time in unsatisfactory condition on most agricultural soils *(Šarapatka, Bednář, Novák 2010, Lhotský et al.* 1984, Lhotský 2000). Good agricultural practices together with sustainable organic farming conserve and/or restore soil properties. Soil biodiversity is crucial for soil properties improvement. Improvement of soil structure expressed as soil aggregates stability is direct evidence of good agricultural practices on soil sustainability to compaction.

At present time when it is evident that soils especially agricultural ones are under stress, the complex methods of soil cultivation in accordance with sustainability principles are needed. This complex of rules called regenerative agriculture has more and more followers and supporters.

Regenerative agriculture as a conservation and/or rehabilitation approach to farming and food systems is coming out from the main soil sustainability principles – topsoil and subsoil protection, conservation and when necessary also regeneration, biodiversity increase focused mainly on soil biodiversity, preserving and improving the water cycle including increase of water holding capacity, enhancing ecosystem services, enhancing carbon sequestration and thus increasing resilience and adaptation of soil to climate change. Comprehensively summarized, regenerative agriculture supports soil health.

According to the World Economic Forum (2022) regenerative agriculture is needed because of several reasons:

Currently, traditional agriculture is in the process of intensification including the use of heavy machinery, fertilizers and pesticides to maximize food production. All these factors contribute to not only soil degradation and loss but also to the degradation of the whole environment as soil is integral part of it.

Within 50 years, there may not be enough soil left to feed the world, according to regenerative farming organization "Regeneration International".

Intensive farming also releases CO_2 naturally stored in soil into the atmosphere. This contributes to the global warming that is driving climate change.

Agriculture accounts for over a third of greenhouse gas emissions globally, according to the United Nations (UN) (Crippa *et al.* 2021).

Damaged soil compacted and eroded land can make environments more vulnerable to extreme weather events and can contribute to the probability of such events like flooding, which are increasing in frequency and intensity as the Earth warms.

It is necessary to use soils in a way that leads to the preventing further soil degradation and preserving its functions to keep natural and/or high level of ecosystem services to observe the following rules:

- when soil is used and its functions are exploited, action has to be taken on soil use and management patterns, and
- when soil acts as a sink/receptor of the effects of human activities or environmental phenomena, action has to be taken at source.

Restoring degraded soils to a level of functionality consistent at least with current and intended use is always more costly than preventing degradation. Considering the cost implications of the soil and environmental restoration can help to use soils in a balanced, thus sustainable way.

CONCLUSIONS

This study evaluated the soil compaction reasons and natural susceptibility of soils to compaction. Susceptibility does not automatically mean that soil is compacted. The real status of the soil's compaction was not a subject of this study because of the lack of actual data and because of the non-stable character of this threat. The study was based on the use of existing data from Slovakian soil database and ESDAC, Vers. 2, available from JRC's European Soil Data Centre. Selected parameters, relevant to the evaluation of soil susceptibility to compaction have been set up and evaluated separately. Different combinations of selected parameters according to a pedotransfer rule were the basis of the evaluation process. A basic premise was set up: every soil as a porous medium could be compacted. This means that soils without natural susceptibility to compaction do not exist. It is important to use soil with the emphasis of sustainability principles and to look for ways to achieve them.

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