Report on the Map of
Natural Susceptibility of Soils to Compaction

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IMPORTANT NOTE

(Marc Van Liedekerke,19/10/09)

This report is still in a draft stage and is not to be considered an official document; the JRC is still working on finalizing it.

1. INTRODUCTION

1.1 The Aim and Purposes of the Map construction

An actualized version of the Map of Natural Susceptibility of Soil to Compaction has been elaborated for evaluation and delineation of priority areas connected to soil compaction at European scale. Soil compaction together with erosion, organic matter decline, salinisation and landslides belongs to the main threats to soil. For these threats the risk area has to be delineated as mentioned in the Thematic Strategy for Soil protection adopted by European Commission on 22 of September, 2006. Knowing priority areas will help politicians as well as soil managers and environmentalists to manage soil use in these areas in such a way that the compaction-threat can be prevented or diminished.

This soil compaction map is exclusively dealing with soil susceptibility to compaction, which is very important for prevention purposes and does not show the real status in European soils. The reasons for this are that there are not enough data for a real status evaluation and significant changes in soil environment during the year when also the real status of soil concerning soil compaction is changing and might be the reason of possible discrepancies in making decisions how to manage touched soils.

For the map at European scale, the *soil susceptibility* to compaction is more realistic and useful for taking proper sanitary, preventive and management decisions.

1.2 Soil Threats as mentioned in Soil Thematic Strategy

The status of European soils is mainly the result of human activities over the past millennia. Only soils in some forests are not influenced by man. The whole area of agricultural soils is influenced by human activities. Cultivation essentially changes the soil environment. Although the aim of cultivation is always to improve soil properties to increase crops, the result is not always in accordance with the aim. Especially in the case of intensively used agricultural soils is the time needed for soil to come in balance with the surrounding environment, either after cultivation or harvesting, very often not enough long. In case of forest soils, intensive works can destroy soil balance as well. As a consequence of intensive or not proper use, soil is very often expressed to many threats. Some threats are connected and one threat can accelerate another one, e.g. compaction can accelerate soil erosion. Almost all of the soil threats are the result of human activities, or their intensity is influenced by man and it is now our task to reduce their occurrence and eliminate their influence on soil. Prevention is of course the best solution and can be realised via sustainable soil use in balance with the surrounding environment. The most harmful is soil sealing, e.g. for building areas, because in this case soil looses the majority of its functions and soil properties. Soil threats lead to soil degradation or even soil destruction. The "*EU Thematic Strategy for Soil protection*" aims to protect soil functions, both natural, resulting from pedogenesis, and/or retrieved by human activities in the process of soil management and fertility improvement via cultivation. It is necessary to identify the areas that are at risk of irreversible or significant degradation by the major threats to soil: erosion, decline of organic matter, landslides, salinisation and *compaction.* The aim is to prevent further deterioration of soil properties as well as to stop the further spreading of the threats. The mentioned threats are soil- and area-specific.

1.3 Definition of Soil Compaction Threat and Soil Susceptibility to Compaction

Soil compaction is 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 even missing in comparison with the arrangement of similar but not compacted soil. The orientation, size and shape of soil aggregates are evidence of compaction of the soil. Aggregates are arranged with the longer side in a horizontal way (platy structure), they do not have a round shape but one side is much longer than the other and, depending on intensity of compaction, they can be totally destroyed if the compaction is too severe.

Soil susceptibility to compaction 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 and a set of external factors like climate, soil use, etc.

There can be different reasons for soil compaction and soil susceptibility; they are divided into two main groups: *natural* and *man induced* as well as one subgroup: *combined* which is the result of the two previous occurring simultaneously at the same place.

Specific soil properties, the surrounding environment and climate are natural reasons for soil compaction. This type of compaction is called also *primary compaction*.

The type of soil use or soil management are man induced reasons for soil compaction. This type of compaction is called *secondary compaction.* In many cases secondary compaction is induced in planned way, e.g. in civil engineering and it is not considered as a negative effect; in the other types of soil use such as forestry and agriculture, soil compaction is considered as negative result of improper soil use and there are efforts to remove it and soil compaction is considered in these cases as *soil threat*.

It is necessary to stress that the *prevention of soil compaction is the most important factor* to combat this soil threat because the compaction itself can negatively influence the other parts of the environment and can create significant damage to soil functions [2]. Compaction is also costly because it decreases significantly crops and can influence even soil productivity. Both cases could have economically serious implications. Also the removal of secondary soil compaction can be very costly depending on the intensity of soil damage.

The prevention of soil compaction is linked to the evaluation of *soil susceptibility to compaction*. Soil susceptibility to compaction can also be divided, similarly to compaction, into two main parts: natural and man induced susceptibility. It is important to know which soil is susceptible to compaction in order to be able to apply proper soil use and cultivation, to prevent real compaction.

From environmental point of view is soil compaction a soil threat and has it has a negative effect not only on soil functions but also on the other parts of the environment. It has this typical feature of soil threats that it can induce or accelerate the other soil threats - mainly erosion and; when erosion occurs in big extent as mass movement, also landslides.

1.3.1 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 [5]. 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 the *texture* and *soil type*.

1.3.1.1 Soil texture and physical properties

Soil susceptibility to compaction is influenced predominantly by its texture, mainly by the clay fraction (size <0.002 mm). The higher the clay fraction, the more susceptible the soil to compaction. Soil texture influences consecutively the other soil properties. Susceptibility to compaction goes in the direction sandy – loamy sandy – sand loamy – loamy –clay loamy – loam clayey – clayey soils – clays. Clays are the most susceptible to natural compaction [10] 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 high weight. They have high water holding capacity because of high content of clay minerals with high surface and interlayers, 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”.

1.3.1.2 Soil water regime and ground water presence

The soil *water regime* influences the soil 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. 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 [8]:

1. Water regime of soils with permafrost.
2. Percolative and periodically percolative water regime (P/PET>1 and P = PET respectively). In case of percolative water regime, the evapotranspiration from soils is lower than infiltration during the major part of the year. The movement of water in the soil profile is mostly descending. In case of periodically percolative water regime, periods with evapotranspiration, higher than infiltration, alternate with periods of lower evapotranspiration and higher infiltration.
3. Impercolative 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* (6) 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 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 (Fluvisols, Gleysols and Histosols).

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

1.3.1.3 Chemical properties

From the chemical soil properties, the most important 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 unfavourable for soil aggregate stability, thus low pH soils are more susceptible to compaction.

1.3.1.4 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, which change can influence soil biota, are: temperature, water and air regime, amount and redistribution of available nutrients (occurrence mainly in upper parts of topsoil, the rest of soil profile without nutrients, water and air), pH and Eh, soil density (earthworms). Low humus or organic matter content can increase soil susceptibility to compaction in case of medium heavy or heavy soils, however sandy soils are an exception from this rule: in general, sandy soils, having a low humus or organic matter content, have also low susceptibility to compaction.

1.3.1.5 Arrangement and kind of soil horizons

Accumulation of clay in a so called "argillic horizon" is a driving force for the formation of compaction features in the soil. 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 podsolisation and illimerisation, and clay movement decrease the soil structure stability and influence water movement in a 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 WRB. Qualifiers serve a more detailed evaluation of soils and many of them are typically associated to the reference group. In WRB there are prefix and suffix qualifiers. Especially qualifiers related to chemical, physical, mineralogical and textural characteristics can significantly influence the susceptibility to compaction of reference soil groups. Qualifiers can change the final susceptibility of particular individuals in the reference soil group.

For the evaluation of soil susceptibility to compaction, the reference soil group in combination with second level units has always priority on the evaluation of just the reference group level.

Natural origin of soil compaction leads very often to compaction in the whole profile or in its deeper parts.

1.3.2 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 the 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 increases significantly 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. Forest soils, especially during works with wood, like skidding after cutting down the trees, are exposed to crossings by heavy machinery in any type of weather and under any soil moisture content condition. In the case of agricultural soils, the creating of narrow ditches and ploughing of soil can especially create soil compaction. In all of these cases the soil balance with the surrounding environment is broken and usually there is not enough time to come into the same balance again. The renewed or new balance is less stable than the natural one and soil susceptibility to compaction can than 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 loose their natural functions.

A basic rule (for good agricultural practice) when estimating the proper time for ploughing is that **soil moisture content during ploughing has to be around 0.9 of the field capacity** [7]. 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.

Table (1): The axle load of most frequently used agricultural machinery (according to Minnesota Extension service [1])

TYPE OF MACHINE	AXLE LOADS (TONNES)
Slurry tanker, 15.9m^3	10-12
Slurry tanker, 27.25m^3	17-18
6-row combine, empty	10
12-row combine, empty	18
12-row, full with head	24
About 25m^3 grain cart, full, 1 axle	22
Beet cart, full	24
Grain cart, about 42m^3, 1 axle	35-40
Grain cart, about 42m^3, 2 axles	17-20
4WD Tractor, about 271 kW, front axle	13

4WD Tractor, about 167 kW, front axle	7.5
MFWD Tractor, 125 kW, rear axle	6.5

In Table 2 is general soil moisture according to the textural categories (after Šútor in 9) 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.

Agrotechnics today demand 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 amount 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.

Table (2) General soil moisture according to the textural category and proper soil moisture for cultivation; both in % of volume.

SOIL TEXTURAL CATEGORY	SOIL HORIZON (m)	θ_S	θ_{FC}	PROPER SOIL MOISTURE for cultivation (0.9 θ_{FC})
		(% 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:* θ_s *– full saturation of soil profile by water;*
θ_{FC} *– moisture content at field capacity*

The balance of such soil is very fragile because of the high amount of possible soil degradation; 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 process.

Table (3): Predicted crop yield losses and increased tillage costs due to soil compaction on the plough layer and in the subsoil [4]

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
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

Soil susceptibility to compaction is evaluated according to the two main principles and their combination – principle 3 (see Figure 1).

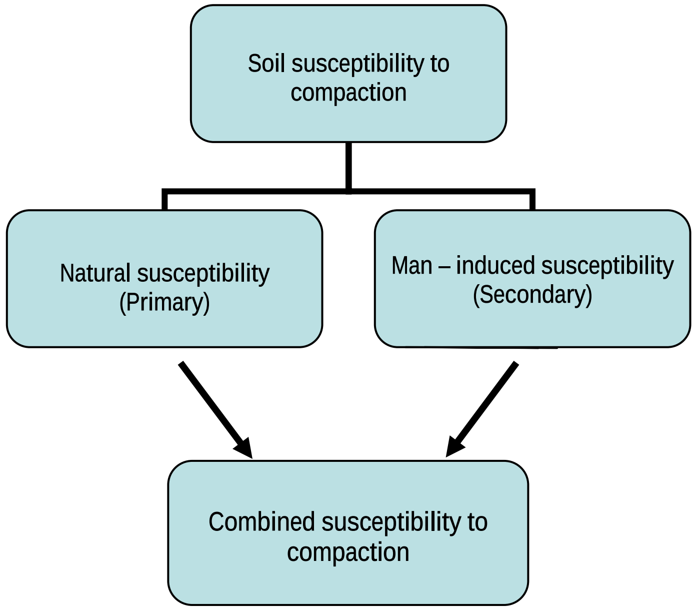

Figure 1. Three types of soil susceptibility to compaction

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.

2. MATERIAL AND METHODS

2.1 The method of the evaluation of natural soil susceptibility to compaction for the purpose of map construction

This method for map construction is based on the creation of logical connections between chosen parameters having importance in the process of the evaluation of soil susceptibility to compaction. These logical connections – *pedotransfer rules* – have been created by use of the parameters taken from the European soil database - ESDB [3], distribution version 2.0. (http://eusoils.jrc.it/Website/eusoils/sg_attr.htm). The database itself is divided into four parts:

1. the Soil Geographical Database of Eurasia at scale 1:1 M (SGDB)
2. the Pedotransfer Rules Database (PTRDB)
3. the Soil Profile Analytical Database of Europe (SPADE)
4. the Database of Hydraulic properties of European Soils (HYPRES).

For the purposes of map construction, the SGDB part of the ESDB database was used.

The database contains a list of Soil Typological Units (**STU**). They represent soil names (WRB 1998) and are described by variables (attributes) specifying the nature and properties of the soils: e.g. the texture, the water regime, the stoniness, etc. STU's represent semantic dataset. The geographical representation was chosen at a scale corresponding to the 1:1,000,000. STU's are grouped into Soil Mapping Units (**SMU**) and form soil associations within the landscapes. Each SMU corresponds to a part of the mapped territory and as such is represented by one or more polygons in a geometrical dataset (Table 4).

Table (4): Soil Geographical database of Eurasia (SGDB4_0.dbf)

COLUMN NAME	DESCRIPTION
SMU	SMU number
STU_DOM	STU number of the STU which is dominant in this SMU (i.e. the STU with highest PCAREA value for this SMU ; if there are equal maximum PCAREA values for two or more STU's, one of them is randomly chosen
PCAREA	How much area of SMU is occupied by the STU_DOM; expressed in percent

There are common rules between STU's and SMU's. On the map, each SMU has to be presented at least in one polygon. Each SMU has to contain at least one STU and on the contrary each STU has to be presented at least in one SMU. The relationship between SMU's and their STU's is described in the STU.ORG table.

Table (5): Soil Typological Units organization (STU.ORG)

NAME	DESCRIPTION	TYPE	SIZE
SMU	Soil Mapping Unit (SMU) identifier.	Integer number	7
STU	Soil Typological Unit (STU) identifier.	Integer number	7
PCAREA	Percentage of area of the Soil Mapping Unit (SMU) covered by the Soil Typological Unit (STU).	Integer number	3

The process of map construction was divided into three steps:

- STEP 1: selection of relevant parameters from SGDB
- STEP 2: evaluation of selected parameters
- STEP 3: creation of Pedotransfer rules

STEP 1: Selection of relevant parameters from SGDB

Parameters for the development of the *pedotransfer rules* have been selected according to the actual database content and their relevance for the compaction evaluation. Soil type, texture and water regime are the most important parameters from the SGDB used in the process of natural soil susceptibility to compaction. Soil types are classified according to the international "World Reference Base for Soil Resources (WRB) classification from the year 1998. The reason for this is the fact that also the STU's in the database are evaluated according WRB (1998). The list of chosen parameters is in the Table (6).

Table (6): Main Parameters of SGDB used in pedotransfer rules

CODE	PARAMETER
AGLIM1	The most important limitation to agricultural use of the STU
AGLIM2	Secondary limitation to agricultural use of the STU
WRB-ADJ1	First soil adjective code of the STU from the World Reference Base (1998)
WRB-FULL	Full soil code of the STU from the World Reference Base (1998)

TEXT-SRF-DOM	Dominant surface textural class of the STU
TEXT-SRF-SEC	Secondary surface textural class of the STU
TEXT-SUB-DOM	Dominant subsurface textural class of the STU
TEXT-SUB-SEC	Secondary subsurface textural class of the STU
TEXT-DEP_CHG	Depth class to a textural change of the dominant and/or secondary STU
WR	Dominant annual average soil water regime class of the soil profile of the STU

Additional to the main parameters, also "auxiliary" parameters have been used for the purpose of making the evaluation more accurate in questionable cases. Some parameters which are auxiliary in the evaluation of the natural soil susceptibility to compaction can be main parameters in the process of the secondary soil compaction evaluation.

Table (7): Auxiliary Parameters of SGDB used in Pedotransfer rules

CODE	PARAMETER
IL	The presence of an impermeable layer within the soil profile of the STU
ROO	Depth class of an obstacle to roots within the STU
WM1	Normal presence and purpose of an existing water management system
USE-DOM	Dominant land use of the STU
USE-SEC	Secondary land use of the STU

STEP 2: Evaluation of selected parameters

Main parameters

The evaluation of selected parameters was done according to the expert knowledge of their properties and influence on soil susceptibility to compaction. Susceptibility of single parameters was divided into three categories:

1. L – low
2. M – medium

3. H – high

Not evaluated (NE) and not relevant categories: NE and NR are also in the dataset.

NE category is represented by soils in the towns and soils disturbed by man. These soils have not been evaluated because of lack of information. It does not mean automatically that they can not have natural susceptibility to compaction even if it is expected that secondary one will play a key role in their case. Also combined susceptibility to compaction will predominate here over natural.

In *NR* category are the localities not relevant for such evaluation: water bodies, marshes, glaciers and rock outcrops.

An evaluation of selected parameters is in following tables:

Table (8): Evaluation of susceptibility to compaction on the level of main reference soil groups

WRB (1998)-GRP CODES AND THEIR MEANING / SUSCEPTIBILITY TO COMPACTION								
AC	Acrisol	M	GL	Gleysol	H	SC	Solonchak	H
AB	Albeluvisol	H	GY	Gypsisol	M	SN	Solonetz	H
AN	Andosol	L	HS	Histosol	L	UM	Umbrisol	L
AT	Anthrosol	NE	KS	Kastanozem	L	VR	Vertisol	H
AR	Arenosol	L	LP	Leptosol	L	1	Town	NE
CL	Calcisol	L/M*	LV	Luvisol	H	2	Soil disturbed by man	NE
CM	Cambisol	M	PH	Phaeozem	L	3	Water body	NR
CH	Chernozem	L	PL	Planosol	H	4	Marsh	NR
CR	Cryosol	M	PZ	Podzol	M	5	Glacier	NR
FL	Fluvisol	M	RG	Regosol	L	6	Rock outcrops	NR

**calcisols can have medium susceptibility in case of argic or vertic horizon presence*

The main principles of the evaluation of soil susceptibility to compaction according to soil groups are resulting from the properties of group specific, profile forming horizons, from water regime and localization of soil groups in the terrain.

Table (9): Evaluation of the susceptibility to compaction on the level of soil subunits (WRB_ADJ) present in the SGDB

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
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	lv	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

**LOW- in case of diffuse form of secondary carbonates; *HIGH – in case of cutans and nodules*

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. Gleyic Umbrisol. On the contrary, high susceptibility of soil to compaction according to the main group decreases if in the profile of such soil a horizon with low susceptibility is present, e.g. Mollic Gleysol.

Table (10): Evaluation of soil susceptibility to compaction according to soil texture

TEXTURAL CODES IN ESDB	DESCRIPTION	EVALUATION
0	No information	NR
9	No mineral texture (Peat soils, rocks, etc.)	L
1	Coarse (clay <18 % and sand >65 %)	L
2	Medium (18 % < clay < 35 % and sand > 15 %, or clay <18 % and 15 % < sand <65 %)	M
3	Medium fine (clay <35 % and sand <15 %)	M/H*
4	Fine (35 % < clay < 60 %)	H
5	Very fine (clay > 60 %)	H

**final evaluation can be influenced by amount of organic matter and sand*

Soil texture plays a key role in 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. In the ESDB both dominant and secondary soil textures are available for topsoil (TEXT_SRF) and for subsoil (TEXT_SUB). In ambiguous cases the secondary texture can influence the final evaluation decision.

The depth to textural change (TEXT-DEP-CHG) was used as additional information in the process of soil texture evaluation because in itself it does not give an explicit result. Especially, soils with shallow depth to textural change represent a less stable environment in comparison with soils without textural change or when it occurs in deeper parts of the profile (80, 120 cm).

Table (11): Depth to the textural change in soil profile (ESDB)

TEXT-DEP-CHG CODES AND THEIR MEANING		EVALUATION
0	No information	NR
1	Textural change between 20 and 40 cm depth	H
2	Textural change between 40 and 60 cm depth	H
3	Textural change between 60 and 80 cm depth	M
4	Textural change between 80 and 120 cm depth	L
5	No textural change between 20 and 120 cm depth	L
6	Textural change between 20 and 60 cm depth	H
7	Textural change between 60 and 120 cm depth	M

Textural change in the profile influences many soil properties, mainly permeability, water regime and redistribution of moisture in both cases: coming from the top (source: irrigation, rain water) as well as coming from the bottom (source: ground water table). Usually deeper horizons have finer texture as horizons above them, but there are many cases where it is opposite.

Table (12): Evaluation of soil susceptibility to compaction according to primary and secondary limitation to agricultural use (AGLIM)

AGLIM codes	Description	Evaluation
0	No information	NR
1	No limitation to agricultural use	L
2	Gravelly (over 35 % gravel diameter < 7.5 cm)	NE
3	Stony (presence of stones diameter > 7.5 cm, impracticable mechanization)	NE
4	Lithic (coherent and hard rock within 50 cm)	M/H*
5	Concretionary (over 35 % concretions diameter < 7.5 cm near the surface)	H
6	Petrocalcic (cemented or indurated calcic horizon within 100 cm)	L/M/H*
7	Saline (electric conductivity > 4 mS.cm-1 within 100 cm)	H
8	Sodic (Na/T > 6 % within 100 cm)	H
9	Glaciers and snow-caps	NR

10	Soils disturbed by man (i.e. landfills, paved surfaces, mine spoils)	NE
11	Fragipans	H
12	Excessively drained	L
13	Almost always flooded	H
14	Eroded phase, erosion	NR
15	Phreatic phase (shallow water table)	H
18	Permafrost	H

**final evaluation of AGLIM depends on the texture of above lying soil horizons*

Limitation to agricultural use gives also information of limitation for plant growth in general. This is the reason why this parameter is also included into the evaluation of natural soil susceptibility. Categories connected to the use of agricultural machinery limitation have not been evaluated (2 and 3) as well as category 10: Soils disturbed by man. The codes are the same also in case of secondary limitation to agricultural use. Limitations to agricultural use with codes 16 and 17 (duripan and petrofferic horizon) are not present in the ESDB database.

Water regime (WR) is in the ESDB presented in classes as dominant annual average soil water regime class for a given STU. Table 13 shows classes of WR and their evaluation according to class influence on soil susceptibility to compaction.

Table (13): Dominant annual average soil water regime classes on STU level and their influence on soil susceptibility to compaction

CLASS	DESCRIPTION	EVALUATION
0	No information	NR
1	Not wet within 80 cm for over 3 months, nor wet within 40 cm for over 1 month	L*
2	Wet within 80 cm for 3 to 6 months, but not wet within 40 cm for over 1 month	M/H*
3	Wet within 80 cm for over 6 months, but not wet within 40 cm for over 11 months	H
4	Wet within 40 cm depth for over 11 months	H

**final evaluation depends on soil texture as well*

The susceptibility of soil to compaction according to water regime class must be evaluated together with other parameters, mainly soil texture and soil type, because it does not give explicit evaluation. Especially, evaluation of the class 2 depends on soil texture.

Auxiliary parameters

The depth to impermeable layer and depth class of an obstacle to roots within the STU are auxiliary parameters used in combination with main parameters, mainly texture and water regime. The ESDB database contains information concerning the location of the impermeable layer and the layer of obstacle for roots, however the reason for this situation is not mentioned, e.g. rock, extreme values of pH, toxic environment, etc. Because of this, the information concerning these parameters can be used according to the assumption that a decrease of soil depth decreases also the stability against external influences (e.g. weather in general, but particularly heavy rain, floodings, etc.) and diminishes or excludes the area for plant roots development. Soil without continuous plant cover is more susceptible to the influence of external factors. This influence is happens mainly in negative direction, which means the deterioration of soil properties.

Table (14): Depth of impermeable layer (IL) in soil profile of the STU in ESDB database

IL CODES AND THEIR MEANING		EVALUATION
0	No information	NR
1	No impermeable layer within 150 cm	L
2	Impermeable layer between 80 and 150 cm	L
3	Impermeable layer between 40 and 80 cm	M/H*
4	Impermeable layer within 40 cm	H

**final evaluation depends on soil texture*

The presence of impermeable layer in category 3 creates high susceptibility of soil to compaction when the soil texture for a given STU is in textural category 3, 4 or 5 (see Table 10).

Table (15): Depth class of an obstacle to roots of the STU

ROO CODES AND THEIR MEANING		EVALUATION
0	No information	NR
1	No obstacle to roots between 0 and 80 cm	L
2	Obstacle to roots between 60 and 80 cm depth	M
3	Obstacle to roots between 40 and 60 cm depth	H
4	Obstacle to roots between 20 and 40 cm depth	H
5	Obstacle to roots between 0 and 80 cm depth	H
6	Obstacle to roots between 0 and 20 cm depth	H

The depth class of an obstacle to roots was evaluated according to the same assumption as the depth to impermeable layer.

Soil use and presence of water management system were used as auxiliary premise parameters and have not been directly evaluated as the other parameters.

Soil use (code **USE-DOM**) describes the dominant and the most apparent land use for a STU. A second type of land use can also be taken into account (**USE-SEC).** Not all soil use categories from SGDB have been used in the process of soil susceptibility evaluation. Just those, which are directly connected with the natural environment, e.g. forest, halophyte grassland, grassland (see Table 16), have been selected. The premise is that each selected land use (land cover) has specific properties which create also specific soil properties.

Table (16): Selected categories of land use from ESDB

USE-DOM AND USE-SEC CODES AND THEIR MEANING	
1	Pasture, grassland, grazing land
2	Poplars
4	Wasteland, shrub
5	Forest, coppice
9	Bush, macchia
10	Moor
11	Halophile grassland
22	Wildlife refuge, land above timberline

Information concerning existing water management was directed to the presence and purpose of an existing water management system (code **WM1**) and not to the type of the system. Such information includes the presence and purpose of an existing water management system in agricultural land on more than 50 % of the STU.

Table (17): Presence and purpose of an existing water management system

WM1 CODES AND THEIR MEANING	
0	No information
1	Not applicable (no agriculture)
2	No water management system
3	A water management system exists to alleviate waterlogging (drainage)
4	A water management system exists to alleviate drought stress (irrigation)
5	A water management system exists to alleviate salinity (drainage)

6	A water management system exists to alleviate both waterlogging and drought stress
7	A water management system exists to alleviate both waterlogging and salinity

Water management system information was used together with information concerning soil water regime (Table 13).

STEP 3: Creation of Pedotransfer rules

Pedotransfer rules have been created for the evaluation of the natural soil susceptibility to compaction within the STU's of given SMU's. The main premise is that every soil, considered as a porous medium, can be compacted.

Pedotransfer rules comprise the **basic assumption**:

IF the soil represents a given soil unit (WRB_GRP) with a given soil subunit (WRB_ADJ) and has a specific topsoil texture (TEXT_SRF) and a specific subsoil texture (TEXT_SUB) with a given depth to textural change (TEXT-DEPTH-CHG) and with a given water regime (WR)[1], and if there is or there is not a limitation to agricultural use (AGLIM)[2], THEN the soil has low, medium, high or very high natural susceptibility to compaction.

[1] WR can possibly be evident also from a given water management system (WM1)

[2] AGLIM can possibly be evident also from the depth to impermeable layer(IL) and the depth to the layer having obstacle for roots development (ROO)

Selected parameters of the ESDB have been evaluated according to this basic premise and natural soil susceptibility to compaction was set up for the purpose of map construction. The greatest simplification was in two marginal situations:

1. -If all selected parameters show high susceptibility to compaction, than the soil has a very high final susceptibility to compaction;
2. -If all selected parameters show low susceptibility to compaction, than the soil has a low final susceptibility to compaction.

For case 1, in the final evaluation, parameters with high susceptibility have been evaluated with higher value as it was in 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 as environment.

The map output

The map was created in ArcGIS program, version 9.2, using ArcMap and is stored as a shape file with attributes table. An example of attributes is in Table 18.

The Attribute table contains attributes of evaluation. FID, Shape, Area and Perimeter belong to the program attributes.

Database attributes have been used for either compaction susceptibility evaluation or can be used to detect area of given compaction.

The database attributes

EUESBN
It is identification of the record.

EUESBN_ID
Identification number.

SMU
Soil mapping unit.

STU1, STU2, STU3
Soil typological unit. Number 1 represents dominant – the STU with the largest area in given SMU, 2 – second largest STU in given SMU, third largest STU in given SMU.

PCAREA1, PCAREA2, PCAREA3
Area in % of STU 1, STU 2 and STU 3.

TOTAREA
Total area of the STU's in given SMU.

DOMAREA
Area of dominant STU. It equals to PCAREA1.

STU
Dominant Soil typological unit.

WRB_GRP
Code for soil group from the World Reference Base (WRB) for Soil Resources.

WRB_ADJ
First soil adjective code of the STU from the World Reference Base (WRB) for Soil Resources.

USE_DOM
Code for dominant land use of the STU.

USE_SEC
Code for secondaryland use of the STU.

AGLIM1
Code of the most important limitation to agricultural use of the STU.

AGLIM2

Code of a secondary limitation to agricultural use of the STU.

TEXT_SRF_D
Dominant surface textural class of the STU.

TEXT_SRF_S
Secondary surface textural class of the STU.

TEXT_SUB_D
Dominant sub-surface textural class of the STU.

TEXT_SUB_S
Secondary sub-surface textural class of the STU.

TEXT_DEP_C
Class of the depth to textural change in the soil profile.

ROO
Code for the presence and depth to the layer of obstacle for roots.

IL
Code for the depth to impermeable layer of the STU.

WR
Dominant annual average soil water regime class of the soil profile of the STU.

WM1
Code for normal presence and purpose of an existing water management system in agricultural land on more than 50% of the STU.

WM2
Code for the type of an existing water management system.

PMAT
Code for parent material.

WRB
Code for soil group from the World Reference Base (WRB) for Soil Resources and first soil adjective code of the STU.

EVALUATION
Code for natural susceptibility of soil to compaction.

Codes of individual attributes can be found also on the web page of EUSOILS: http://eusoils.jrc.it/ESDB_Archive/ESDBv2/popup/sg_attr.htm.

Table (18): Attribute table of the map shape file

ATTRIBUTES OF EVALUATION	EXAMPLE
FID	0
SHAPE	Polygon
AREA	313758411.40600000000

PERIMETER	138989.77279500000
EUESBN_	2
EUESBN_ID	1
SMU	71642
STU1	70072
PCAREA1	100
STU2	0
PCAREA2	0
STU3	0
PCAREA3	0
TOTAREA	100
DOMAREA	100
STU	70072
WRB_GRP	PZ
WRB_ADJ	hi
PAR_MAT_DO	6200
PAR_MAT_SE	0
USE_DOM	0
USE_SEC	0
AGLIM1	1
AGLIM2	1
TEXT_SRF_D	1
TEXT_SRF_S	1
TEXT_SUB_D	0
TEXT_SUB_S	0
TEXT_DEP_C	5
ROO	1
IL	1
WR	1
WM1	0
WM2	0
PMAT	6
WRB	PZhi
Evaluation	1

Note: Data input for the creation of the final map comes uniquely from the SGDBE component of the European Soil Database – version-2 available from http://eusoils.jrc.it/ESDB_Archive/ESDB_Data_Distribution/ESDB_data.html ; practically, the attribute table SGDBE4_0.dbf of the shapefile SGDBE4_0.shp has been linked to the dbf file STU_sgdbe.dbf (though the dom_STU attribute), interpreting the data in “dominant STU” fashion. This joined table has been used then in consecutive elaborations.

3. RESULTS

The map of natural soil susceptibility to compaction was created from the evaluation of selected parameters from the ESDB.

The soil susceptibility to compaction was divided into 4 categories. Two additional categories represent the data concerning places where this evaluation was either not relevant or could not been provided because of lack of information. In total there are 6 categories:

0 – no soil

1 - low susceptibility to compaction

2. - medium susceptibility to compaction

3. - high susceptibility to compaction

4. - very high susceptibility to compaction

9. – no evaluation possible

Category 0 – no soil: represents water bodies, glaciers and rock outcrops. Category 9 – no evaluation possible: was the case of towns including also soils, soils disturbed by man and marsh. For these situations, evaluation was not possible because of lack of relevant data.

3.1 Soils with naturally low (L) susceptibility to compaction

In the case of low susceptibility to compaction the following soil units and subunits are present:

AN: ANao, Andy, ANhi, ANhu, ANth

AR: ARha, ARpr

CH: CHcc, CHch, CHgs, CHha

CL: CLad, ha

CM: CMca, CMcr, CMdy, CMeu, CMge, CMhu, CMmo, CRan,

FL: FLca, FLdy, FLeu

HS: HSdy, HSeu

KS: KScc, KSha

LP: LPca, LPdy, LPeu, LPha, LPhu, LPli, LPmo, LPrz, LPum

LV: LVar, LVcc, LVcr, LVha

PH: PHca, PHha

PZ: PZet, PZha, PZhi, PZle, PZum

RG: RGca, RGdy, RGeu, RGha

Um: Umar

These soil units and subunits have predominantly coarse or medium texture and water regime class 1 or 2. Soils with medium fine or fine texture can not have water regime other than 1. Soils with water regime class 3 or 4 are not present in this category.

3.2 Soils with naturally medium (M) susceptibility to compaction

Soil units and subunits having medium susceptibility to compaction:

AB: eu, st, ha, gl

AC: ha

AN: dy, hu

AR: ab

Ch: cc, ha

CM: ca, cr, dy, eu, ge, gl, mo, vr

CR: cc, ha, tu, um

FL: ca, dy, eu

GL: ca, dy, eu, ha, mo

HS: dy, eu

KS: ha

LP: ca, dy, eu, ha, mo, rz

LV: ab, cc, cr, dy, fr, gl, ha, vr

PH: ab, ca, gl, ha, lv

PL: dy, mo

PZ: cb, gl, ha, le, pi, rs

RG: ca, dy

VR: cr, pe

These soil units and subunits have predominantly medium and medium fine texture and water regime class 1 or 2. Supplementary parameter – water management has in many cases code 3: "a water management system exists to alleviate waterlogging (drainage)" or code 6: "a water management system exists to alleviate both waterlogging and drought stress".

3.3 Soils with naturally high (H) susceptibility to compaction

Soil units and subunits having high susceptibility to compaction:

AB: gl, ha, hi

AC: gl

AR: ha

CH: lv

CL: szn

CM: ca, dy, eu, gl, vr

CR: gl, hi

FL: ca, dy, eu, mo, um

GL: ca, dy, eu, hu, mo, so

GY: ad

HS: cy, dy, eu, fi, ge, sa

KS : cc

LP : ha, rz

LV : ab, cr, cc, gl, ha

PH ; gl, lv

PL : dy, eu, mo

PZ : gl, ha, pi, um

RG : ca

SC : gl, ha

SN : ha, mo

UM : gl

VR : cr, pe

These soils are mainly in textural categories 3, 4 and 5. Main limitations for them are either excess of salts, shallow water table or they are flooded. The water regime class has all categories: 1, 2, 3 and 4. In case of category 1 there is another limitation, mainly excess of salts.

3.4 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 the water regime class is often 3 and 4. In the case that the water regime class is 1 or 2, the soils are saline and heavy. In general, soils are mainly in textural categories 3, 4 and 5.

Soil units and subunits:

AB: ha

CH: cc

CM: cr

FL: ca, dy, eu, gl, hi, sz, ti, um

GL: eu, hi, hu, mo, ti

HS: cy, dy, eu, fi, ge, sa, sz

KS: lv

LV: cr, gl, ha

PH: gl, lv

PL: lv

PZ: gl, um

SC: gl, ha

SN: gl, mo, VR: ha, pe

Two maps dealing with natural susceptibility of soil to compaction have been created: map with all soils and map showing agricultural soils.

4. CONCLUSIONS

This study evaluated the 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 ESDB, 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 (see tables in chapter 2). 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.

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