A method to assess the vulnerability of agricultural subsoils to compaction

Matthias Lebert

Soil Scientist and Consultant, Kiel, Germany, Email Matthias.Lebert@t-online.de

Abstract
The method proposed consists of three steps to derive the vulnerability of subsoils to compaction. In the first step, the mechanical susceptibility to compaction is determined by the pre-compression stress with pedotransfer functions. In the second step, soil structural quality of subsoils is determined by the evaluation of soil physical properties as air capacity, saturated water conductivity and packing density. In the third step, vulnerability to compaction is derived by combining the mechanical susceptibility to compaction with the soil structural quality. The method is based on the evaluation of actually analysed soil physical data from 1300 representative agricultural subsoils in Germany, offered by the soil surveys of the federal states. The results are shown in maps of 1:1.000.000 scale. At the water content of 100 % field capacity, about 60 % of the German subsoils are high vulnerable to compaction, including marshlands, clayey river sediments, glacial loams, loessian soils, periglacial clays and loamy and clayey soils derived from weather beaten rocks and sediments. Pure and loamy sands have low vulnerability. At the water content of 80 % field capacity, low, medium and high vulnerability are distributed about one third each over the arable area in Germany.

Key Words
Soil compaction, soil structure, soil protection strategies, soil risks mapping

Introduction
Compaction reduces fertility, aeration and permeability of soils. It impairs soil functions and is regarded as a soil threat that can become a risk for sustainable land use. Soil compaction is subject of various national and international legislative frameworks. In order to set up national and international soil protection strategies, maps for the identification and quantification of the risk of subsoil compaction are essential.

Methods
Soils and data
The investigations were done at a random sample of 1300 representative subsoils of arable land in Germany. The analytical data of the soils were offered by the soil surveys of the German federal states. The majority of the sampling has been done after 1990. The following data were used for evaluations: geological origin of the soil, soil type, soil horizons, packing density, texture, skeleton, organic matter content, dry bulk density, air capacity, available water capacity, non-available water capacity, saturated water conductivity, cohesion and angle of internal friction.

Assessment of susceptibility to compaction by pedotransfer functions
In Germany, three sets of pedotransfer functions exist to assess the mechanical pre-compression stress of soils (DVWK M 234 1995; DVWK M 901 2001; DIN V 19688 2001). Lebert (2008) verified the following functions for general use to German agricultural subsoils: DVWK M 234 for pure and loamy sands and DIN V 19688 for silts, loams and clays and for silty and clayey sands. The verified functions were used in the paper to derive pre-compression stress and the corresponding susceptibility to compaction, which are classified according to a proposal by Lebert and Schäfer (2005) (Table 1).

Table 1. Classification of pre-compression stress and of the susceptibility to compaction

Pre-compression stress			Susceptibility to compaction
kPa	Class Nr.	Name of class	Name of class
< 80	5	very low	very high
80 - < 120	4	low	high
120 - < 160	3	medium	medium
160 - < 200	2	high	low
≥ 200	1	very high	very low

According to the verified pedotransfer functions Lebert (2008) determined the pre-compression stress for typical, representative subsoils in Germany, and developed a simplified classification scheme, depending on the soil texture and the packing density of the soils (Table 2). According to that scheme, the susceptibility can be mapped in any scale.

Table 2. Class of susceptibility to compaction at the water content of field capacity (pF 1,8) of German subsoils depending on soil texture group (Ad Hoc AG Boden 2005) and packing density (PD).

Soil texture group	Class of mechanical susceptibility to compaction PD 1	PD 2	PD 3	PD 4	PD 5
pure sands	5	3	1	1	1
loamy sands	5	4	2	1	1
silty sands	5	5	4	3	2
sandy loams	5	5	4	3	3
sandy silts	5	4	4	3	2
loamy silts	5	4	3	3	2
clayey silts, normal loams	5	5	4	4	3
clayey loams	5	5	5	4	4
silty clays, loamy clays	5	5	4	4	4

Table 2 shows the susceptibility to compaction at the water content of field capacity (pF 1,8) by pedotransfer functions for the pre-compression stress. To consider the effects of desiccation on susceptibility of soils an algorithm was used, proposed by Rücknagel (2006) (Table 3). The reduction of the susceptibility class at field capacity (pF 1,8) is depending on the initial class and on the degree of desiccation in % field capacity. No further reductions are made to the lowest class of susceptibility (class 1 = very low).

Table 3. Reduction of the class of susceptibility to compaction depending on the degree of desiccation in % of field capacity.

Initial class at field capacity (pF 1,8)	Reduction of susceptibility class to compaction in classes at % field capacity: 90	80	70	60	50
5	-1	-1	-2	-3	-4
4	-1	-1	-2	-3	-3
3	-1	-2	-2	-2	-2
2	-1	-1	-1	-1	-1
1	no reductions on lowest class				

Assessment of soil structure quality

Soil structure quality in this paper is defined as the quality of those soil functions that are strongly and directly affected by compaction, i.e. soil aeration, soil permeability and rootability.

Table 4. Classification of soil structure quality.

a) Packing density (-)	b) Air capacity (% vol.)	c) Saturated water conductivity (cm/d)	Class	Name of class	Class of soil structure quality
≥ 1,8	< 5	< 10	5	very low	Round off from
1,7 - < 1,8	5 - < 7	10 - < 40	4	low	average of classes a),
1,6 - < 1,7	7 - < 13	40 - < 100	3	medium	b), c) =
1,4 - < 1,6	13 - < 26	100 - < 300	2	high	
< 1,4	≥ 26	≥ 300	1	very high	(a + b + c) / 3

In this paper, a set of thresholds is used as proposed by Lebert *et al*. (2007). A set of three parameters, air capacity, saturated water conductivity and packing density, allows the detection of soil structure damage by compaction. A distinct identification of soil structure damage is possible when all three parameters exceed the limits of a sufficient soil structure at the same time: the air capacity is less than 5 % (vol.), the saturated water conductivity is below 10 cm/d, and the soil is classified into classes 4 (= dense) or 5 (= very dense) by the soil structure valuation of packing density. The classification of soil structure quality in this paper corresponds to these thresholds in the class "very low" (Table 4). The further classification corresponds to the ratings of the German soil survey (Ad Hoc AG Boden 2005). The class of soil structure quality is calculated as a round off from the average value of the single parameters.

Assessment of vulnerability to compaction
The classification of the vulnerability of subsoils to compaction is done by a combination of the two above described parameters: soil structure quality and mechanical susceptibility to compaction. It follows the principle that vulnerability is high, when soil structure quality is low and simultaneously, the mechanical susceptibility to compaction is high. There are 5 classes of vulnerability to compaction, very high = 5, high = 4, medium = 3, low = 2 and very low = 1. The result is a 1:1 weighed average of the class of susceptibility (Tables 2 and 3) and the soil structure quality class (Table 4). In Table 5, three examples for the determination of the vulnerability class are given.

Table 5. Examples for the determination of the class of vulnerability to compaction.

a) Class of susceptibility (Table 2)	b) Water content (% field capacity)	c) Reductions in classes by water content (Table 3)	d) Final class of susceptibility	e) Class of soil structure quality (Table 4)	Class of vulnerability (1:1 average of d) and e), round off)
4	100	0	4	4	(4 + 4)/2 = 4,0 = 4
4	70	-2	2	3	(2 + 3)/2 = 2,5 = 3
2	90	-1	1	3	(1 + 3)/2 = 2,0 = 2

Results

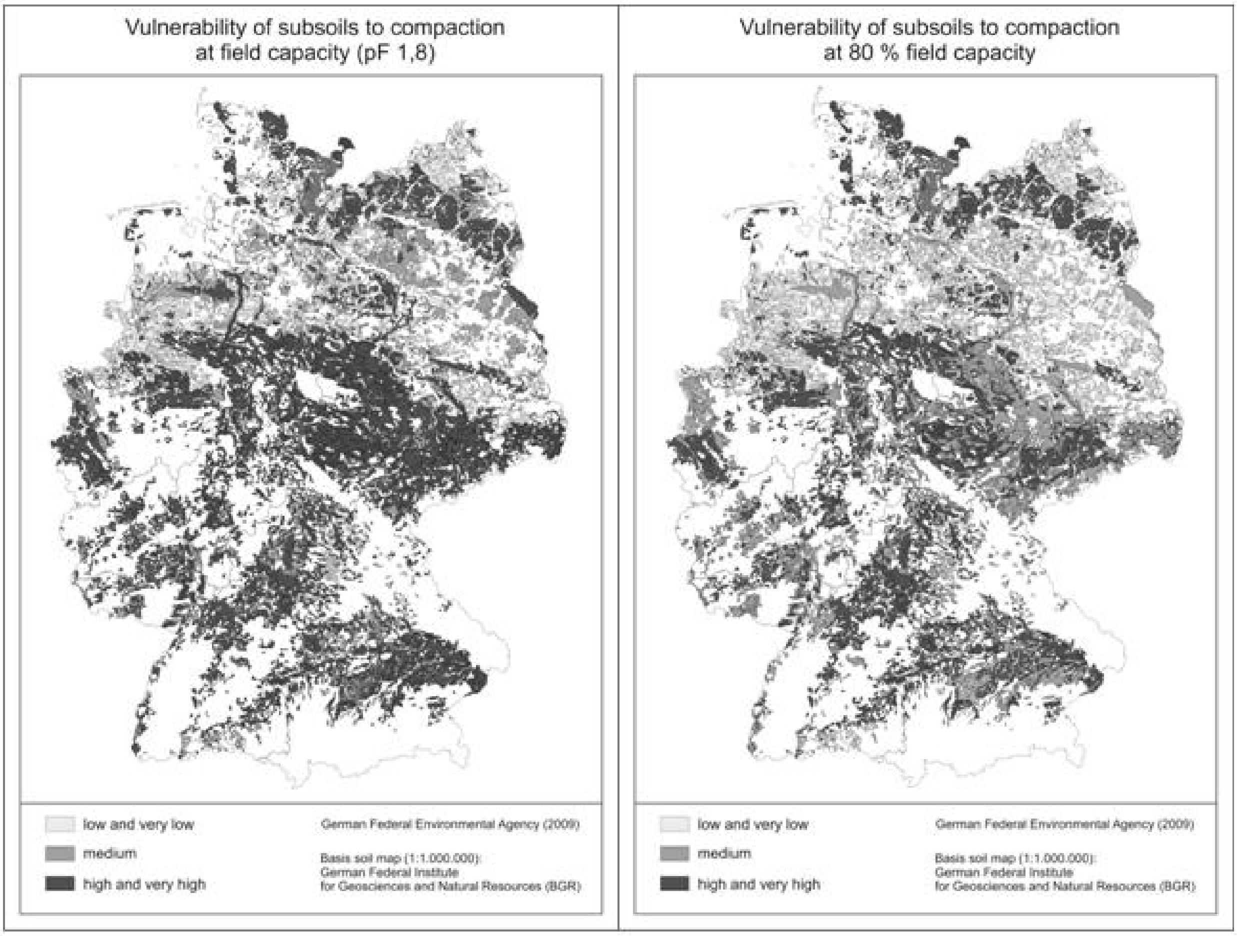

Figure 1. Vulnerability to compaction of agricultural subsoils in Germany in the map 1:1.000.000 at two water contents: field capacity (pF 1,8) and 80% field capacity.

Figure 1 shows the results of the assessment of vulnerability to compaction at two different water contents: 100 % field capacity (= pF 1,8) and 80 % field capacity in the 1:1.000.000 map of Germany. Around 60 % of the German agricultural subsoils are high and very high vulnerable to compaction at the water content of field capacity. Nearly all loamy, silty and clayey soils are representing these classes. Poor loamy sands have medium vulnerability and only pure sands are classified as low vulnerable. The vulnerability at field capacity can be considered as a worst case, because the real water content in subsoils during field operations is lower than field capacity. A water content of 80% field capacity is likely to be more representative during wheeling in subsoils. At that water content, each of the classes "low and very low", "medium" and "high and very high" nearly represent a third of the German arable land. Pure sands and poor loamy sands are low and very low vulnerable. Medium vulnerable are loessian sands, loess soils mixed with weather beaten materials, loessian soils of loamy silty texture, loamy and clayey soils derived from weather beaten rocks and hard sediments with high amount of skeleton, silty river sediments and periglacial silts. High vulnerable are soils of the marshlands, clayey river sediments, glacial loams, loess soils with clayey silty texture, periglacial clays, loamy and clayey soils derived from weather beaten rocks and hard sediments with low amount of skeleton (< 25 % Vol.) and loamy moraines.

Conclusion

The results of mapping in the 1:1.000.000 scale show, that large areas of German arable land are highly susceptible and vulnerable to compaction. The results underline the importance of the protection of soils against compaction. The avoidance of subsoil compaction is evident for a sustainable land use, because subsoil compaction is a high risk for soil functions. For the prevention of soils against compaction soil physically based approaches to adjust the mechanical stresses to the subsoils mechanical strength are mandatory.

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