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RISK ASSESSMENT METHODS OF COMPACTION

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RAMSOIL

Risk Assessment Methodologies for Soil Threats

Introduction

A negative trend in modern mechanized agriculture is the ever increasing wheel loads. Van den Akker et al. (2003) concluded that European soils are more threatened by compaction than ever in history. In arable land with annual ploughing, both topsoil and subsoil compaction should be considered. From the short-term economic and environmental point of view topsoil compaction has more impact than subsoil compaction. However, from the sustainable point of view subsoil compaction is the most serious threat. This was also the conclusion of the Soil Strategy Working Groups (Van Camp et al., 2004). It should be noted that in the definition of subsoil used by Van den Akker et al. (2003) and Van Camp et al. (2004) the so-called plough pan or hard pan is the upper part of the subsoil, and in most cases the most severe compacted part of the subsoil. Soil tillage and natural loosening processes can remedy topsoil compaction and within some years a good soil quality is regained. Subsoil compaction is an ongoing cumulative process, leading in the end to homogeneously compacted subsoil. The resilience of the subsoil for compaction is low and subsoil compaction is at least partly persistent (Allakukku, 2000, Voorhees, 2000). There is a strong relation between compaction and erosion and flooding because topsoil and subsoil compaction reduce the water infiltration capacity of soil seriously. Therefore, in the risk assessment compaction in general is addressed, although in the Thematic Soil Strategy the soil compaction threat is associated with the subsoil.

Evaluation criteria

In a compaction risk assessment three factors affecting soil compaction should be considered: (1) climate, (2) soil and (3) soil and water management (Canarache, 1991, Van Ouwerkerk and Soane, 1994, Van den Akker, 2002).

Ad 1. Climate: The higher the rainfall and the lower the evapotranspiration, the higher the water infiltration capacity must be. Wet soils are weak and can be compacted easily. Shrinkage by drying is a very important mechanism for self-loosening and restructuring of soils. The same accounts for freezing, although the impact on subsoil compaction is disappointing (Håkansson and Petelkau, 1994). Soils that stay wet have a low resilience to compaction because they do not shrink and biological loosening activities are hindered.

Ad. 2 Soil: Strength, compactability and resilience depend on texture, clay mineralogy, humus content, soil moisture content, structure and soil fauna. Essential soil physical properties such as hydraulic conductivity, diffusivity of oxygen, penetration resistance for roots, air porosity are reduced by compaction. Soils are considered overcompacted if some of these soil physical properties are below certain threshold values. Compactability depends on texture, structure, density and moisture content, which determine the strength of a soil. Resilience of overcompacted soils depends on among others on shrinkage capacity, biological activity and loosening by tillage. The shrinkage capacity depends on clay and humus content. Biological activity depends strongly on humus content, structure, density and moisture content. Loosening by tillage can be very effective, however, destroys the structure, is detrimental for soil biota and makes the soil very susceptible to recompaction. Especially recompacted subsoils can have a degraded structure and poor soil physical properties (Dexter et al., 2004, Kooistra et al., 1984).

Ad 3. Soil and water management: A poor drainage situation or irrigation at the wrong moment can make the soil wet and in that way vulnerable for compaction. Soil and crop management is an important factor in the compaction risk assessment. Wheel load and tyre inflation pressure must be in agreement with the strength of the soil. In many cases this is not possible for the topsoil and in too many cases also the subsoil is compacted. The resilience and possibilities for loosening of the topsoil are good, however, this is not the case for the subsoil. Manuring and harvesting during wet periods can be very harmful. Ploughing with two wheels in the open furrow causes subsoil compaction. Intensive crop rotations with a high percentage of root crops that is harvested late in autumn (e.g. sugar beet) with heavy machinery is a high risk factor. On the other hand a high percentage crops such as cereals, that have the capability to improve the soil structure are beneficial. Also the ownership is important. Owned land is treated better than hired land.

Evaluation RAMs found in literature

Canarache (1987), Canarache et al., (2000) and Petelkau et al., (2000) included most of the factors mentioned in the preceding paragraph by using a semi-empirical approach in a compaction risk assessment for Romania respectively Eastern Germany. These assessments are based on many long term experiments, additional measurements of e.g. compactability and a lot of information in well developed databases and a good interpretation of the data including development of pedotransfer functions. The developed assessments are adjusted to the national situations and available data and are not directly suitable for other countries.

Horn et al., (2005), Simota et al., (2005) and Van den Akker (2004) used a more deterministic approach in compaction risk assessment by comparing calculated strengths of a series of soils with stresses excerpted by a wheel load. A recent development of this family of compaction risk assessment methods is the Alcor model (www.microleis.com). Compaction risks at two moisture ratios were classified for topsoil and subsoil according the soil strength, maximum allowable wheel load/inflation pressure or the effect on soil physical properties. Pedotransfer functions including a structure classification based on mainly German measurements were used to calculate soil strengths. This assessment is used to construct maps from farm scale up to European scale (Horn et al., 2005). An advantage of this deterministic method is that is can be used in every country, although it is doubtful whether pedotransfer functions for German soils can be used in a country with a completely different climate and/or soils. Another disadvantage is that the used pedotransfer functions are not all based on readily available data.

Jones et al., (2003) used readily available data from the European Soil Database and climatic data stored in the agrometeorological database of the MARS project. This data was combined with a classification of vulnerability based on expert judgment derived in profile pit observations on a wide range of soils in mainly intensive farmed areas. The analyses resulted in a provisional map of inherent susceptibility of subsoils in Europe to compaction. Jones et al., (2003) concluded that better and actual climatic data and quantitative results of soil mechanical research should be incorporated in their approach. Another large scale approach to assess mainly the existence but also the risk for compaction concerning Eastern Europe is the SOVEUR project (Nachtergaele et al., 2002). In this project experts of the respective countries mainly base the assessment approach on expert judgment. This expert judgment can be based on sophisticated methods as indicated above, but also on subjective impressions. This possible difference in quality of the assessment is a weak point in this method.

It can be concluded that most compaction risk assessment methods are mainly based on a determination of the vulnerability of soil for compaction and only partly include other factors as climate and water- and soil use management. Also the resilience of soil for compaction is only partly included. In this respect, semi-empirical methods have the advantage that they inherently include these aspects. However, their disadvantage is that they are rather region dependent and are based on experiences in the (recent) past. The consequence is the use of these semi-empirical methods is doubtful in case changes in land management or climate occur.

Returned questionnaires

In total 17 questionnaires on compaction were returned. Figure 1 shows the countries that returned the questionnaires on compaction. Figure 2 presents to which extent the RAMs have an official status. It should be noted that all RAMs in Germany, Denmark, France, Romania and Spain and the proposed RAM in Finland are based on the same deterministic approach (Horn et al., 2005, Simota et al., 2005). The two questionnaires from Belgium are in fact a questionnaire from Wallonia and a questionnaire from Flanders. Wallonia has no RAM and the RAM of Flanders is in development. The four responses of Germany are from the federal government, an advisor on soil compaction RAMs, the state of Thüringen and the state of North Rhine Westfalia. Each state of Germany has its own policy how to deal with the implementation of the federal laws and European directives.

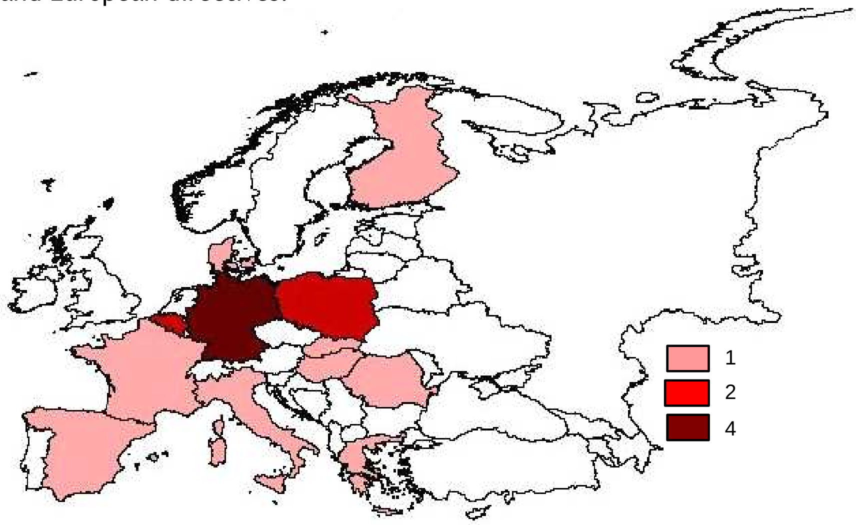

Figure 1. Return number of compaction questionnaires.

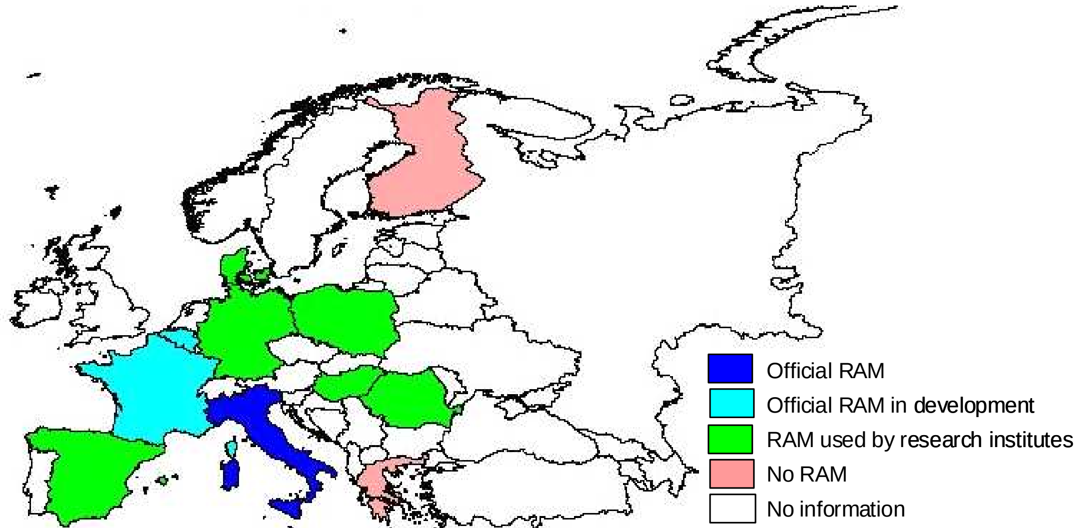

Figure 2. Status of the compaction RAMs in the EU.

Results questionnaires and discussion

In Table 1 the information used for the risk assessment of compaction is indicated per country. In Table 2 the thresholds considered in the RAMs are presented. Together with the literature referred to in the questionnaires it was possible to get a good impression of most of the RAMs. First the RAMs are considered which are mainly based on a deterministic approach. Then the RAMs are considered which are mainly based on direct measurements and experience.

Table 1. Information used in the risk assessment of compaction.

CRITERIA																		
Country		Romania	Germany	Germany	Germany	Germany	Poland	Poland	Denmark	France	Spain	Greece	Italy	Finland	Slovakia	Hungary	Belgium	Belgium
Quest number		3A	4A	4B	4C	4D	5A	5B	6A	9A	11A	12A	18A	20A	23A	24A	25A	25B
RAM available?	Yes, Official, Development, Institute	Y, I	Y, I	Y, I	Y, I	Y, I	Y, I	Y, I	Y, I	Y, D	Y, I	No	Y, O	No	Y, I	Y, I	No	Y, D
STU	Soil typological unit	X	X	X				X	X	X	X	X			X	X	X	X
Land use	e.g. LUCas	X		X					X	X		X		X	X	X	X	X
Equipment use	Weight, Wheel Load, Inflation Pressure, Tyre type	WL, IP	W, WL, IP, Ty	W, WL, IP, Ty			IP		W, WL, IP, Ty	W, WL, IP, Tyre	WL, IP	W		W, WL, IP				
Land cover	e.g. Corine	X							X	X							X	X
Topography	Digital elevation model			X							X	X						
PTF	Pedotransfer functions used:	X	X		X	X		X		X	X						X	
PTF +	Land Cover, Land Use, Spatial Soil Info, Model, GIS	GIS, LC, SSI, Model	GIS	Model + GIS	GIS	LC		Model + GIS	Model + GIS	Model, GIS	Model, GIS	LC, LU					GIS + SSI	
Texture		X	X	X	X	X		X	X	X	X	X		X	X	X	X	X
OM		X		X	X	X		X	X	X	X	X		X		X	X	
Density	Bulkdensity dry, Bulkdensity at fc, Packing Density, Porosity, Degree of	Bd, Bfc	Bd, PD	Bd, PD	Bd, PD	Bd, Bfc, PD	Bd, DegComp			Bd,	Bd, Bfc	Bd, Bfc, Por			Bd	Bd, Bfc		
Moisture	Field Capacity, Wilting Point, Water content sat, Workability Limit, Infiltration cap. sat	FC, WP, Wsat, WL, Ksat	FC, WP, Ksat	FC, WP, Ksat, Infil_sat	FC	FC, WP, Wsat, Ksat	FC, WP, Wsat, Ksat	FC, WP, Wsat, WorkL, Ksat	FC, pFcurve	FC, Wsat		FC, WP, Wsat		Ksat	FC, Wsat	FC, WorkL, Ksat		
Drainage class		X								X		X					X	X
Air	Air capacity, Air conductivity, Diffusion		Acap	Acap, Diff	Acap	Acap, Acond	Acap, Acond, Diff	Acap						Acond, Diff	Acap			
Mechanical	PreCompression stress, Shear Strength, Penetration resistance	PreC, ShearS	PreC, ShearS	PreC	PreC, ShearS	PreC	Pen	Pen, PreC	Pen, PreC	PreC, Compress-ibility	PreC	Pen				Pen		
Climate	Precipitation, Temperature, Radiation, Potential Evapotranspiration, yearly, seasonal, monthly, 10 days, daily	P-m, T-m		P-s		P-s, PE-s	P-y, P-s, T-j, T-s		R-d, PE-d	P-d, T-d, PE-s	PE-m	P-y, P-m, T m, R-y, R-m, PE-y, PE-s		R-10, PE-s		P-y, P-s, P-m, P-d, T-y, T-s	P-y	
Climate +	Land Cover, Land Use, Spatial Soil Info, Model, GIS	GIS, LC, SSI, Model				LC			GIS + Model	Model	Model, GIS	LC, LU						

Table 2. Thresholds and threshold values used in the risk assessment of compaction

THRESHOLDS																	
Country	Romania	Germany	Germany	Germany	Germany	Poland	Poland	Denmark	France	Spain	Greece	Italy	Finland	Slovakia	Hungary	Belgium	Belgium
Quest number	3A	4A	4B	4C	4D	5A	5B	6A	9A	11A	12A	18A	20A	23A	24A	25A	25B
RAM available?	Y, I	Y, I	Y, I	Y, I	Y, I	Y, I	Y, I	Y, I	Y, D	Y, I	No	Y, O	No		Y, I	No	Y, D
Water content	Workability limits					FC			X	Workability limits	X			35 vol%			
Saturated hydraulic conductivity		10 cm/d	10 cm/d		10cm/d								24 cm/d				
Air capacity		5 vol%	5 vol%		5 vol%	10 vol %								10 vol%			
Oxygen diffusion rate			1			<30 µg m^{-2} s^{-1}											
Penetrometer values						2-3 Mpa					X			2,8-6,0 MPa	2,8-3,0 MPa		X
Precompression stress	> Load	> Load	> Load					> Load	> Load	> Load							
Dry Bulk Density						1.4-1.5 Mg m^{-3}			X		X			1,35 - 1.7 g cm^{-3}	1,5 g cm^{-3}		
Bulk Density at Field Capacity					Klassen 4/ 5 (dicht/ sehr dicht)						X						
Packing Density		class 4 and 5 (DIN 19682-10, Germany)	X		Klassen 4/ 5 (dicht/ sehr dicht)	X											

Deterministic RAMs
Most RAMs presented have mainly a deterministic approach. Note that not all needed information used in the institutional RAMs in Germany, Denmark, France, Romania, Spain and the proposed RAM in Finland is the same, although all are based on more or less the same deterministic approach (Horn et al., 2005, Simota et al., 2005). The Alcor model (*http://www.irnase.csic.es/users/microleis/microlei/manual1/alcor/alcor3.htm*) and the SIDASS model (Horn et al., 2005, Simota et al., 2005) are the latest versions of this family of RAMs based on a deterministic approach. Of these two the SIDASS model is the most complete one considering wheel loads, strength of the subsoil, climatic conditions, drainage conditions, land cover and soil properties, and using GIS and databases to derive maps presenting risk areas for compaction. An usual way to show which areas are at risk for subsoil compaction is to present the strength of the subsoil. The stronger the subsoil is, the lower the risk of subsoil compaction. An example of such a presentation is shown in Figure 3.

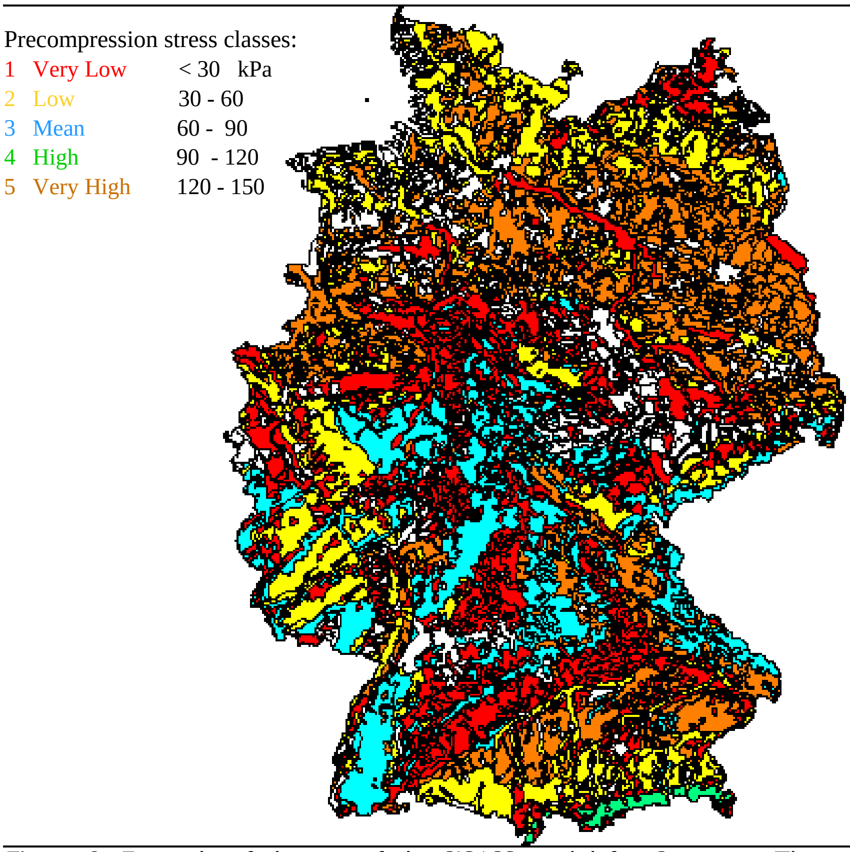

Figure 3. Example of the use of the SISASS model for Germany. The strength of a wet subsoil (soil water suction 6 kPa) is expressed as precompression stress.

Next step in the procedure is to compare the strength of the subsoil with the stresses on the subsoil exerted by a wheel load with a certain tire with a certain inflation pressure. In this way for a particular combination of tire and tire inflation pressure the maximum wheel load that just does not compact the subsoil can be calculated for each subsoil in a country. This has been done by e.g. Van den Akker (2004) for the Netherlands. The concept that the stresses in the subsoil should not exceed the strength of that subsoil means that no additional compaction is allowed, even if some compaction is not harmful to the most important soil qualities. Also the resilience of soil to compaction, so the natural regeneration of soil qualities by among others shrinkage, soil biota and rooting, is neglected. On the other hand an already highly compacted subsoil will be much stronger than a not overcompacted subsoil with a still satisfactory soil structure and soil (physical) properties. In fact this would mean that the farmer that created highly overcompacted subsoil is “rewarded” because now he can use much higher wheel loads than his neighbor with a healthy, however, weaker subsoil. The neglecting of the resilience of subsoils and the “rewarding” of the farmer with overcompacted subsoils was reason for Lebert et al. (2007) to propose a procedure in addition to the calculation of maximum allowable wheel loads, in which the soil qualities are checked of soils that are overloaded and compacted. Beside the soil physical soil qualities presented in column 4A in Table 1 also the visual inspection of the soil structure and the determination of the packing density in this way is part of the procedure. In the French RAM in development also the increase in bulk density by compaction will be calculated and compared with threshold values (G. Richard, personal communication 2007). These threshold values for the dry bulk density are in development and will be calibrated with the aid of a monitoring system in development in which several soil physical properties are measured and also soil biodiversity is monitored. Together with available data this monitoring will produce relations between increased bulk density and important soil physical such as saturated hydraulic conductivity and air capacity.

Altogether the latest RAMs and the French RAM are very complete considering the cause of subsoil compaction, the reaction of the soil, the influence of climatic conditions and drainage conditions, the impact on important soil physical properties and to a certain extent the resilience of subsoils to compaction. A very weak point of the existing RAMs is that there has been no good validation of them up to now. The calculated allowable maximum wheel loads are in general rather low, and are in many cases much lower than the wheel loads used in praxis nowadays. For sure several subsoils are overloaded and overcompacted with degraded soil qualities, however, on the other hand in many cases the harm done to the soil seems to be acceptable or not noticeable. Probably the strength of subsoils is underestimated, because in general the static strength of the soil is measured and used in the calculations, while a wheel load is dynamic. In most cases the dynamic strength of a material is higher than the static strength. Another weak point is the lack of data on soil strength. Up to now the major part of data on strength of agricultural soils is collected by the research group of Rainer Horn in Kiel, Germany, and they mainly measured the strength properties of German soils. Positive developments are an increasing amount of measurements of soil strength in many European countries and an increasing amount of countries using and developing RAMs based on more or less the same deterministic approach.

The Italian RAM

The Italian RAM is evaluated separately because it is the only official accepted RAM and it only considers the cause of compaction. This means that the soil is not considered at all. The RAM is described at:
http://www.apat.gov.it/site/_contentfiles/00140000/140076_Annuario_2004_Versione2.pdf
The risk of compaction is evaluated by using a proxy indicator derived from the number and power of tractors (and harvesting machinery) and number of passes on agricultural soil. The indicator is calculated as follows:

$$Sp = kW*P*N*5 / S$$

Where:
Sp = Sum of weights
kW= kilowatt
P = average weight of the machinery = 102 kg·kW (Assuming a linear increase of the weight vs. power : 1kW=102 kg)
N = number of tractors and harvesting machinery
5 =mean number of passes on the field per year
S =hectares of arable land and orchards

The data on machineries is derived from official sources (ISTAT database). Results are comparable in time and space due to the homogeneity of the data sources. The indicator Sp is calculated for each region in Italy. The results Sp are represented over 8 classes (from values in the range 1 - 5, to high values > 141. The strong point of this RAM is it simplicity and the availability of data. A very weak point is that the RAM completely ignores the impact on the soil. It is also not clear what the limiting value for Sp is and how such a limit can be determined.

RAMs based on measurements and experience.
The Polish RAM presented in column 5A of the Tables 1 and 2 is based on the determination of the degree of compactness of a soil. In short: the actual bulk density of a soil is compared with the bulk density of the same loosened soil artificially compacted by a pressure of 1 bar (100 kPa). By measuring also several important soil physical properties of the artificially compacted soil and comparing these with threshold values, it is possible to derive a value for the degree of compactness which implies a soil status with good or reasonable soil physical qualities (Lipiec et al., 1991, Lipiec and Håkansson, 2000, Håkansson and Lipiec, 2000, Lipiec and Hatano, 2003). The method is developed for topsoils and it is not clear and probably doubtful whether this method can be used for subsoils, because subsoils are generally not loosened. The method is only used on parcels and not to determine risk areas. These aspects make this RAM less useful for the determination of risk areas.

The second Polish RAM presented in column 5A of the Tables 1 and 2 is an institutional RAM in development and information is only in Polish available. The outcome of this RAM will be a compaction risk map 1 : 100 000 of Poland.

It was difficult to get a good impression of the RAM of the Slovak Republic, because beside the information in the questionnaire only some general information could be derived via a website (www.vupu.sk). Probably the RAM is based on a soil monitoring since 1993. This can be a good basis for the identification of already compacted subsoils and subsoils at risk. The RAM is expert based and requires analyses by an expert. These aspects make that this RAM can only be used in the Slovak Republic although several aspects, such as methods used and some threshold values, can be rather universal. An evaluation of e.g. the effect of changing climate or land use management is difficult because the RAM is mainly based on experience.

The RAM of Hungary is better documented (Birkás et al., 2000 and Birkás et al., 2004). The RAM is based on the evaluation of a soil monitoring since 1976 of parcels in arable use throughout Hungary. In this way a lot of experience is gained about the vulnerability and the actual compaction of Hungarian topsoils and subsoils. This RAM is comparable with the RAM of the Slovak Republik and has the same advantages and disadvantages.

The Flemish Belgian RAM (column 25B in Tables 1 and 2) is in development and no documentation is available yet. The idea up to now is that it will be mainly based on an inventory of the existence of compacted Flemish soils based on an assessment of the penetrometer resistance of representative soils followed by an evaluation.

The results of the questionnaires derived from Belgium (Wallonia, column 25A) and Greece are not further evaluated because they described desired RAMs and were lacking additional documentation.

Conclusions

Most countries in the EU are using or developing a RAM based on a more or less similar deterministic approach. The most developed RAMs are very complete and include the cause of subsoil compaction, the reaction of the soil, the influence of climatic conditions and drainage conditions, the impact on important soil physical properties and to a certain extent the resilience of subsoils to compaction. The deterministic basis of these RAMs makes it easy to use

them in GIS applications and to make use of soil data bases and climate data bases. Harmonization throughout Europe is in one way rather easy, because the structure of the RAMs is in essence the same. However, probably the harmonization of the data and measurement methods and interpretation of measurement results will be much more difficult. A major problem is that none of the RAMs is validated and that input data is lacking. Nevertheless a harmonized RAM based on a deterministic approach will be easier accepted EU wide and easier developed than a RAM based on experience.
The only official RAM from Italy does not consider soil at all and will be probably not acceptable for the soil scientific community in the EU.
National RAMs based on experience and in most cases on large and long lasting monitoring systems are probably very useful for the determination of risk areas in that particular country, however, can not be used in other countries.

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