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Vulnerability of subsoils in Europe to compaction: a preliminary analysis

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Abstract

Identifying the vulnerability of subsoils to compaction damage is an increasingly important issue both in the planning and execution of farming operations and in planning environmental protection measures. Ideally, subsoil vulnerability to compaction should be assessed by direct measurement of soil bearing capacity but currently no direct practical tests are available. Similarly, soil mechanics principles are not suitably far enough advanced to allow extrapolation of likely compaction damage from experimental sites to situations in general. This paper, therefore, proposes a simple classification system for subsoil vulnerability to compaction based for field use on local soil and wetness data at the time of critical trafficking, and, at European level, on related soil and climatic information. Soil data are readily available 'in Country' or from the European Soil Database and climatic data are stored in the agrometeorological database of the MARS Project. The vulnerability to compaction is assessed using a two-stage process. First, the inherent susceptibility of the soil to compaction is estimated on the basis of the relatively stable soil properties of texture and packing density. Second, the susceptibility class is then converted into a vulnerability class through consideration of the likely soil moisture status at the time of critical loadings. For use at local level, adjustments are suggested to take account of possible differences in the support strength of the topsoil and specific subsoil structural conditions. The vulnerability classes proposed are based on profile pit observations, on a wide range of soils examined mainly in intensively farmed areas where large-scale field equipment is employed. A map of soil susceptibility to compaction in Europe has been produced, as the first stage in developing a more rigorous quantitative approach to assessing overall vulnerability than has been possible hitherto.

Key words: subsoil; compaction; soil classification; Europe

1. Introduction

In the context of this paper, 'subsoil is defined as subsurface soil material that lies below the normal annual cultivation depth or pedological A horizon as appropriate'. Knowledge concerning the vulnerability of subsoils in Europe to compaction is an increasing requirement within agriculture and in the planning of environmental protection measures. Once subsoil damage occurs, it can be extremely difficult and expensive to alleviate. Subsoil compaction risks are increasing with growth in farm size, increased mechanisation and equipment size, and the drive for greater productivity. The response of the engineering industry to the demands of agriculture has been impressive over the past 30 years. Larger and larger machines have been developed but, from the soil standpoint, the result has been a significant increase in axle loads not always matched by reductions in ground contact pressures to prevent or minimise compaction. (Renius, 1994; Tijink et al., 1995).

Research into the causes and effects of compaction in topsoils and subsoils in Europe has demonstrated the detrimental effects on the farming system (Hakansson, 1994). It is now clear, however, that the detrimental effects of compaction go far beyond agricultural concerns of restricted root penetration, decreasing yields and increasing management costs. The overall deterioration in soil structure that may result from compaction, aggravated at times by a build up of water above the compacted layer, can also:

1. increase lateral seepage of excess water over and through the soil, accelerating the potential pollution of surface waters by organic wastes (slurry and sludge), pesticides, herbicides and other applied agrochemicals;
2. decrease the volume of the soil system available to act as a buffer and a filter for pollutants;
3. increase the risk of soil erosion and associated phosphorus losses on sloping land through the concentration of excess water above compacted layers;
4. accelerate effective runoff from and within catchments.
5. increase green house gas production and nitrogen losses through denitrification under wetter conditions.

Recently, the Regions in Europe have been charged with the task of developing environmental protection plans and an integral component of these will be soil protection. Compaction, particularly in subsoils, has, therefore, ceased to be a problem only of productive agriculture; the environmental impacts that can ensue are now causing serious concern (Van den Akker, 1999). Assessing the vulnerability of different subsoils to compaction is, therefore, an increasingly important issue. This is not only so that appropriate measures can be identified for its avoidance in different situations, but also to determine the extent of actual and potential problems within Europe.

Whilst the ideal method for assessing the vulnerability of a subsoil to compaction would be to make direct measurements of its support or bearing capacity, no reliable, easily applicable direct tests are available to achieve this. Assessments have to be made indirectly from more readily measured parameters and soil properties. From a research viewpoint, attention to the soil mechanical strength properties, stress/strain relationships and the pattern of structural recovery after compaction is appropriate. The assessment of these properties is, however, particularly involved and to date there is insufficient information available to allow results to be extrapolated widely beyond the research locations themselves (Bullock et al., 1985). Until such information becomes available, guidance on soil vulnerability to compaction must be based on more readily measurable and available information, supplemented by field experience of soil behaviour under load.

The most readily available spatial information on soils in most countries is soil survey data and this can be supplemented with climatic and land use/cover data. A simple scheme, using existing soil and climatic data for assessing the vulnerability of subsoils to compaction in different climatic situations, is described here. Adjustments are also proposed for application of the scheme in local areas but it should be emphasised that any such scheme can only provide general guidance for use on a local or national scale. Modification for local situations must take account of particular local characteristics that could alter any vulnerability class.

At European level, spatial soil data are held within the European Soil Database (Heineke et al., 1998) and climatic data in the agrometeorological database of the MARS Project (Vossen and Meyer-Roux, 1995). Both these databases are located at the European Union's Joint Research Centre at Ispra, Italy. The objective of this paper is to demonstrate the use of these databases for the construction of maps, albeit at small scale, showing areas most vulnerable to subsoil compaction. Such maps should be of immediate value to policy makers. Whilst the European soil and climatic databases have their limitations, they offer a useful starting point. If supplemented with further information at local level, vulnerability assessments could assist in the planning of field operations. Such information is essential for any review of land use systems and this paper aims to take the first significant step towards providing the necessary framework.

2. Soil resistance to deformation and compaction

The degree of soil movement and possible compaction consequences, that occur when a soil is subjected to external loads, depend upon the magnitudes of the loads, the pressures applied and the soil sliding or shearing resistance developed during deformation. (Spoor, 1979). Soil shearing resistance comprises largely of two components whose magnitudes vary between soils and soil conditions. The two components are the frictional and cohesive resistances.

The magnitude of the frictional resistance component is dependent on soil particle type and size distribution, the shape, size and stability of structural units present, and the nature and tightness of their packing (Terzarghi and Peck, 1962). Angular shaped particles and units tend to offer a greater resistance to sliding than rounded particles and the greater the degree of interlocking the greater the resistance.

The cohesive component is very dependent upon soil moisture status and the surface activity of the clay fraction (Spoor and Godwin 1979). Cohesion increases at higher moisture tensions, particularly in the active surface area of the soil particles and units. Chemical and organic bonding forces can be a significant component of cohesion in some soils and these can be influenced by cation type and soil pH. In rapid loading situations, in saturated soils or in cases with similar loadings on saturated structural/shrinkage units, viscosity effects can also influence deformation resistance (Spoor, 2000).

Traffic loadings on subsoils tend to be largely vertical. Air filled horizontal pores and planar voids are much more susceptible to closure than their vertical counterparts and this decreases horizontal permeability. Therefore, soil structural type and fissure/crack-development are important factors controlling the degree of compaction that may occur. The greater the number of vertical macropores for similar soil unit stability and strength, the greater the resistance to compaction. Vertical biopores formed by roots and soil organisms are also extremely resistant to collapse under the action of vertical compressive loads; they do, however, easily succumb to significant horizontal shearing loads. The exception to the normal largely vertical loadings arises through the operation of tractor wheels within the open furrow during ploughing operations. Large horizontal as well as vertical stresses can also be induced through wheel slip in such situations.

In most field situations, subsoils that have been previously stressed over time have responded, through compaction, consolidation and partial recovery, to the stresses applied. The largest of these stresses has frequently originated from numerous in-furrow wheelings during ploughing operations. In some situations, particularly on coarse and medium textured soils, more compact zones may be present below ploughing depth. Although these more compact zones are frequently referred to as ‘pans’, with the assumption that they act effectively as barriers to root penetration and downward percolation of water, this is by no means necessarily the case. These changes and conditions will influence the stress distribution in the subsoil during loading and the aim of subsoil protection measures in current loading situations must be to ensure that, in the absence of unacceptable vertical impedance, new subsoil stresses do not exceed these pre-consolidation/compaction stresses.

During surface loading, topsoil condition in terms of its looseness/firmness/strength will also influence the stresses transmitted to the subsoil. In weak topsoils, considerable wheel or track sinkage can also occur increasing the magnitude of the stresses within the subsoil.

3. Methods

A two-stage methodology is proposed to assess the vulnerability of subsoil to compaction:

1. Assessing the *inherent susceptibility* on the basis of the relatively stable soil properties of texture and packing density.
2. Combining this *soil susceptibility* with an index of climatic dryness/subsoil wetness, or actual moisture status, to determine the *vulnerability* class.

A highly susceptibility soil is one that has properties that make it likely to become compact, given the appropriate compactive forces and the right moisture status.

Knowledge of soil physical properties and moisture status can be particularly helpful in assessing the likely magnitude of the soil shearing resistance and hence the inherent susceptibility and vulnerability of a subsoil to compaction. Those properties most closely related are as follows:

1. Soil texture, estimated from the proportion of sand, silt and clay (% by weight), and expressed as a texture class.
2. Nature of clay fraction and associated ions
3. Bulk density, t m^{-3} (g cm^{-3})
4. Organic matter content, often expressed as percentage organic carbon (by weight)
5. Structure, the type, size and degree of ped development which strongly influence porosity, permeability and nature of macro-pores
6. Soil moisture (water) content (% vol.).
7. Soil moisture potential (kPa).

With the exception of information on clay mineral type and soil moisture content/potential, all the other properties are reported in or can be inferred from soil survey records and databases. In some situations, clay mineralogy can also be inferred from geology or soil parent material or soil structural properties.

The soil moisture content is the most variable of these parameters and, in the case of compaction, the water content at the time of deformation is critical to the amount and extent of compaction that occurs and its subsequent effect on soil physical conditions. On a medium timescale, climate and weather govern the moisture status of soils except in highly receiving sites such as marshes, the lowest parts of river valleys and around lakes, including wetlands. The agrometeorological databases can, therefore, provide valuable information on the overall climatic moisture status for many large-scale situations. At a local level the moisture status at critical loading times is usually known or can be inferred.

3.1 Available soil data for estimating susceptibility to compaction

A number of systems are used in different countries for recording soil information, but, in the European Soil Database, all the soils of Europe are classified according to the FAO-UNESCO (1974) system. Linkages are available for conversions between the different systems, including the revised FAO-UNESCO-ISRIC (1990), where required. In this paper, the FAO-UNESCO (1974, 1990) system is used as the standard so that the results will be applicable to the whole of Europe.

3.1.1 Soil texture

The FAO-UNESCO soil texture classes are shown below in tabular (Table 1) and graphical form (Figure 1). Ideally in future, a more complex scheme of soil texture classes would be advantageous for assessing susceptibility to compaction, for example that of the USDA (Schoeneberger et al., 1998) or the UK (Hodgson, 1997).

3.1.2. Density

Bulk density, measured on undisturbed samples (Hall et al., 1977) for the different soil horizons (layers) in representative profiles, provides the most useful density information for compaction assessment. Unfortunately, data on the density of soils are not readily available because of the time and expense required for making the necessary measurements. Consequently, a pedotransfer rule (PTR) for estimating subsoil density has been developed by Van Ranst et al. (1995), for use where no direct measurements are available.

This PTR at European level integrates an estimate of subsoil structure, assessed as poor, medium or good from pedological inputs such as the FAO *soil name*, to give *packing density* or *Lagerungsdichte* (Renger, 1970). Packing density (PD), which elsewhere in the literature is given the symbol Ld, effectively integrates the bulk density, structure, organic matter content of mineral fraction and clay content, to provide a single measure of the apparent compactness of the soil. Elsewhere, it has proved to be a very useful parameter for spatial interpretations that require a measure of the compactive state of soils (Jones and Thomasson, 1993). In situations where the actual bulk density is known, packing density can be readily determined from equation (1).

$$PD = Db + 0.009C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where Db is the bulk density in t m^{-3}
PD is the packing density in t m^{-3}
C is the clay content (%, by weight)

Three classes of packing density are recognised: low <1.40, medium 1.40 to 1.75 and high > 1.75 t m^{-3}.

Soils with high packing density (> 1.75 t m^{-3}) are generally not very susceptible to further compaction whereas those with medium and low PD (< 1.40 t m^{-3}) are vulnerable at critical moisture contents and loads.

3.1.3. Organic matter

Organic matter contents of mineral subsoils are usually very low (< 2%) and hence are unlikely to have a major influence on subsoil compactability. The exceptions are some Fluvisols (CEC, 1985; FAO-UNESCO, 1974) that by definition are developed in materials recently laid down by river systems, in which organic carbon contents in the subsoils may exceed 2%. Organic soils and some soils with subsurface horizons rich in organic matter (e.g. Humic Podzols) are further exceptions. The packing densities of fluvial subsoils tend to be lower than in non-fluvial subsoils of corresponding texture because fluvial materials are naturally much less compact. Hence density assessments for these soils could require organic matter correction. In practice, the higher organic matter content in Fluvisols does not appear to account for the low density in the subsoil so it is not considered necessary to take organic matter into account in any assessment of susceptibility to compaction.

3.1.4. Structure

International systems for assessing soil structure describe the size, shape and strength of peds (Schoeneberger et al., 1998; FAO-ISRIC, 1990; and Hodgson, 1997). Structure is an important aspect of the overall strength of the soil and hence its susceptibility to compaction. Generally, soils with single grain, granular and weakly developed blocky structures are susceptible to compaction. Strong blocky, prismatic and platy structured soils are not particularly susceptible at low moisture contents but generally the susceptibility of these structures is strongly interactive with moisture content. Another complicating factor is that fine and very-fine textured soils with angular blocky and prismatic structures often have high packing densities. In this respect, these soils can be regarded as naturally compact and, therefore, are not usually susceptible to further compaction as a result of management. For local application, adjustments to vulnerability class may be necessary to take account of specific soil structure situations.

3.2. Soil/climate interactions influencing vulnerability to compaction

The previous section describes the soil physical properties important in assessing the inherent susceptibility of a soil to compaction. However, the strength of any soil at a particular bulk density depends, crucially on its moisture status at the time of loading and deformation (Spoor and Godwin, 1979).

To translate soil susceptibility to compaction into vulnerability, soil moisture contents, topsoil condition and the magnitudes of likely loadings and pressures at critical times must be taken into account. Vulnerability, can be considered as a likelihood that compaction will occur. Considering the moisture component, to establish a scheme or system for classifying the vulnerability of soils to compaction, some direct measure of moisture status or estimate of climatic wetness is needed. A crucial question is: ‘what is the likely moisture content of soils susceptible to compaction at the time of year when field operations such as seed bed preparation, fertilising, slurry spreading and harvesting, are taking place?’ In machinery management terms, compaction risks are frequently greatest during the harvesting period, when the heaviest equipment is likely to be employed. However in climatic terms, risks may be greater in spring when moisture contents are higher than in autumn over much of northern Europe (see Thomasson, 1982; Thomasson and Jones, 1989).

One measure of the climatic conditions influencing soil moisture-state is to assess the excess of evapotranspiration over rainfall during the growing season. This can be a useful index in many situations, particularly with respect to likely moisture conditions during the harvesting period. In practical terms it is necessary to use the potential evapotranspiration, the resulting parameter being called the potential soil moisture deficit – PSMD – (Smith, 1967; Jones and Thomasson, 1985) as defined in Equation (2).

For the period considered:

$$PSMD = \Sigma(R-PE) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

When PE exceeds R

Where: PSMD is the maximum potential soil moisture deficit
R is the rainfall in mm
PE is the potential evapotranspiration in mm.

The PSMD, expressed in mm rainfall equivalent is a measure of the overall maximum dryness of a rainfed system. It is essentially a climatic index independent of soil or climatic variations.

The actual soil moisture deficit is not dependent on weather conditions alone but is also affected by soil water reserves, the crop ground cover, the proximity of a ground water table to the surface and land management practices such as drainage and irrigation. Relatively high water tables during the growing season with associated capillary rise can significantly reduce the soil moisture deficit when compared with the potential value, as can irrigation.

Estimates of the actual soil moisture deficit for specific locations can be obtained by adjusting the potential evapotranspiration for crop type. Jones and Thomasson (1985) propose a method for correcting PSMD for the main arable crops in temperate areas: winter wheat, spring barley, sugar beet and potatoes, and grass. The Crop Growth Monitoring System (CGMS) developed at the Joint Research Centre in the MARS Project (Vossen and Meyer-Roux, 1995) uses a less data demanding methodology based on crop calenders to address the same problem.

There are other parameters suitable for indicating soil moisture conditions. These include the beginning and the end of field capacity (FC), its duration in days (Jones, 1985; Jones and Thomasson, 1985), the timing of likely rainfall following long dry periods and practical experience of water table measurements that indicate subsoil wetness at critical trafficking periods. In irrigated areas, information on likely moisture deficits at specific periods during the year is usually available from irrigation scheduling data. In places where the early spring period is the most critical for tillage or landwork, subsoil moisture contents during that period are usually at or very close to field capacity and hence moisture deficits can be assumed to be zero or very low. This of course may not be the case in southern Europe.

Because of the site-specific nature of the more refined moisture status indices, the potential soil moisture deficit is used in this analysis as the moisture state index. PSMD has proved a particularly useful climatic parameter in the wetter north of the European Continent (Jones and Thomasson, 1993), but its application needs to be tested further in the drier climates of the south, before its adoption for the whole of Europe is justified.

4. Susceptibility and vulnerability classification

There is a general lack of quantitative data on the compactability of different types of subsoil. Classes of susceptibility and vulnerability of subsoils to compaction have therefore been drawn up on the basis of soil advisors' long-term experiences in the field together with data derived from profile pit observations on a wide range of soils, occurring mainly in intensively farmed areas where large-scale equipment is employed.

4.1. Susceptibility classification

Table 2 classifies the inherent susceptibility of subsoils to compaction on the basis of texture and packing density. The classification does not include a soil structure item directly, because in practice subsoil structure and its stability are often closely related to texture and packing density Where deviation from this occurs, due allowance will need to be made directly for the influence of structure. In the classification system proposed, it is considered that any structure within the texture code classes 1,2,3 and 9 is very weak in terms of its potential resistance to subsoil compaction. Strong and coarse structural units are frequently found in the fine and very fine texture classes playing an important role in resistance to compaction and this is taken into account in the susceptibility classes suggested.

The susceptibility classification (Table 2) has been applied to the European Soil Database (Heineke et al., 1998) and a preliminary map, Figure 2, produced, showing the inherent susceptibility of subsoils to compaction. As emphasised, this is only the first stage in assessing the vulnerability of subsoils in Europe to compaction. To complete the process in the future, climatic data must be overlaid on the soil data and furthermore it is necessary to evaluate the impact land use.

Figure 2 shows a provisional distribution of susceptible subsoils in Europe, a distribution which must not be interpreted as actual vulnerability to compaction. A spatial analysis of this distribution has revealed the following proportions for the 4 susceptibility classes: low 20%; moderate 44%; high 28%; very high 9%. Thus more than a third of European subsoils are classified as having high or very high susceptibility to compaction and more than 75% moderate or high susceptibility. The patterns of high and very high susceptibility are mainly associated with areas of coarse or organic soils.

4.2. Vulnerability classification

Table 3 classifies the vulnerability of subsoils to compaction on the basis of inherent soil susceptibility, climatic zone (defined by potential soil moisture deficits and the duration of field capacity, measured in days) and topsoil strength. The influence of the topsoil condition is included, since this can have a significant effect on the degree of 'protection' provided to the subsoil. In situations where the topsoil is loose and weakly structured, or where it is very wet and tends to flow on loading, the vulnerability rating in a number of situations will increase.

The vulnerability classes defined in Table3 must be considered as assessments of average vulnerability under average climatic conditions, with consequent insensitivity for seasonal extremes. At field level, the operator may have access to real soil moisture data and/or antecedent weather data and should be able to adjust the average vulnerability rating accordingly.

Whilst loads and pressures are not incorporated into the above classification, they have been included in a further development by Spoor et al. (in press), specifically to provide soil management/machinery guidelines to minimise the risks of subsoil compaction. The more vulnerable the subsoil the greater the attention that needs to be paid to loads and pressures to which soils are subjected if subsoil compaction is to be avoided.

4.2.1. Application of vulnerability classification

It must be stressed that the vulnerability classification has been developed as a guide to the likelihood of subsoil compaction occurring. It should not, however, be considered as rigid and binding. There are some fine textured (codes 3,4 and 5 in Table 2), low density, weakly structured subsoils with very limited macroporosity, where only a small reduction in this porosity would have a very significant adverse effect on their physical properties. In such cases, whilst the vulnerability classes assigned to these soils would be similar to those of equivalent soils with greater macroporosity, field experience indicates their sensitivity to the effects of compaction would be greater. Therefore choosing a higher vulnerability rating would provide a greater margin of safety against damage at high moisture contents. Conversely, in dense strong coarsely structured soils, it may be possible to reduce the vulnerability rating. The influence of the load, pressure, soil sensitivity and actual field moisture status aspects on vulnerability to compaction is considered in detail in Chamen et al. (in press).

Specific examples identified in Table 4, are taken from a range of soils in the British lowlands that, with the exception of Fladbury Series (a Fluvisol), are under continuous arable cropping and farmed using large-scale equipment. The Susceptibility and Vulnerability Classes identified follow closely field experience in terms of the situations where subsoil compaction problems have been observed. The average potential soil moisture deficits for these soils lie within the 126-200mm climatic zone (Jones and Thomasson, 1985).

The Naburn and Newport (soils (Arenosols) are very easily compacted; compaction pans form very readily and if broken compaction could develop at much greater depths in the subsoil. Subsoil compaction in these soils is, however, easily corrected and the subsoils rarely if ever become anaerobic.

Wisbech , Wick, Romney (12 % clay) and Agney series soils having slightly more clay are less susceptible to subsoil compaction than the loamy sands (Arenosols). The Wisbech and Agney soils in particular have very firm subsoils full of vertical biopores. These biopores are the old root channels of the tidal zone vegetation that grew there during soil formation. They constitute the main pathways for root, air and water movement and are extremely resistant to collapse under vertical loads. However, shear forces disrupt them immediately and hence deep cultivation operations could have a disastrous effect on subsoil quality. All these soils tend to be under intensive cropping involving vegetables and root crops with consequent early and late season trafficking.

Hanslope (35% clay) and Evesham (45% clay) series soils (luvisols) are mainly used for growing combinable crops They are naturally compact and hence very resistant to further subsoil compaction. Their subsoils comprise coarse prismatic structural units which, due to the swelling and shrinking nature of the high clay fraction, remain largely saturated in themselves to moisture contents below permanent wilting point (Spoor and Godwin, 1979).

The Fladbury series clay soil (60% clay) is of low density and frequently extremely wet, but rarely in continuous arable cropping. Being a Fluvisol, its ‘susceptibility to compaction’ rating for a given packing density is increased relative to non-Fluvisols, due to its very low density (see footnote Table 2). Although the subsoil comprises of extremely stable micro-aggregates it is moderately vulnerable to compaction at high moisture contents. Under grassland with a firm topsoil, the subsoil is well protected against damage. Subsoil damage is only likely when subjected to excessively high loads that can cause considerable sinkage under wet conditions.

5. Discussion

An estimate of the area in Europe occupied by soils that are vulnerable to subsoil compaction is currently an urgent requirement. This is necessary to ensure that compaction, in both agricultural and environmental contexts, is considered by policy makers as an on-going, as well as serious, degradational hazard, together with erosion and pollution.

The inherent susceptibility to subsoil compaction, estimated from soil properties, is the first step to assessing vulnerability. The vulnerability classification proposed here is intended for guidance and, at this stage, should not be regarded as definitive. However, modifications to susceptibility and vulnerability classes can be made in specific situations, taking account of local factors and management aspects, as illustrated in the previous section. Particular attention needs to be given to soil wetness at the time of trafficking and to the particular loads and pressures being applied. Whilst the magnitude of axle loads is often emphasised, it is crucial that the importance of ground pressures is given equal attention. Appropriate reductions in contact pressures can, within wide limits, mitigate the effects of high axle loads on the potential for subsoil compaction (Chamen et al., in press)

The only practical means whereby areas at risk of subsoil compaction can be identified at the European level is by building links between the scheme proposed here and the European Soil Database. The computerised geometric and attribute data in this database provide the necessary inputs, at the simplest level, to assess *inherent susceptibility* to subsoil compaction. To obtain vulnerability, climatic data must be ‘overlaid’ on the inherent susceptibility.

The agrometeorological database for the MARS Project, held at the Joint Research Centre, contains data that are suitable for computing a moisture index such as potential soil moisture deficit. The database contains average data on temperature, evaporation and rainfall for 50km x 50km grid squares covering the whole of Europe (for this grid network see Zdruli et al. 2001). These data should provide the basis for generating the potential soil moisture deficit (PSMD) data that are needed to convert *susceptibility* into *vulnerability*. However, for future policy-making and implementation, PSMD will be needed at resolutions better than 50km x 50km, for example 25km x 25km or 20km x 20km. This is because climatic conditions in much of Europe can vary considerably over distances smaller than 50km.

At the next stage of developing a European vulnerability map, it is probably not appropriate to attempt to map the relative differences between the vulnerability classes based solely on the European Soil Database. In the policy-making context, it is probably sufficient to categorise subsoils more simply as either *vulnerable* or *not vulnerable*. A simplified classification indicated in Table 5 is suggested as a basis for this.

It is essential in future that land use and generalised crop cover data are also included in the final vulnerability assessments. Table 6 attempts to portray the impacts of land use and cropping systems, interacting with climatic phenomena to accentuate, or modify, soil loading.

6. Conclusion

On the basis of the existing information described here, any attempt to identify the vulnerability to compaction of subsoils in Europe, on a spatial basis, lends itself to fundamental improvement.

Initially, the main tasks for future improvement of the approach described in this paper are:

1. Combine existing climatic data (at 50km x 50km intervals) with inherent soil susceptibility data to produce estimates of subsoil vulnerability to compaction.
2. Improve the resolution of the agrometeorological data at European level, preferably to 25km x 25km;
3. Incorporate the quantitative results from recent soil mechanics-research (Van den Akker, 1999, Van den Akker and Canarache, 2001);
4. Use pedotransfer functions based on the latest research, for example those computed by Horn and Fleige (2000).

The relevance of this type of modelling, applied through a soil map at 1:1,000,000 scale, may be questioned. It may be more appropriate at scales of 1:50,000 or larger, where real crop performance in specific fields, or where detailed management interventions, are being evaluated. It is clear that the basic data to run such models at scales larger than 1:1,000,000 will be lacking for some parts of Europe for many years to come. In the absence of these data, however, the approach described in this paper offers the best chance of achieving results that are satisfactory enough for broad scale policy-making in the immediate future.

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Table 1. Texture and particle size grades used by the FAO soil classification system

Code	Class	Particle size grades
1	Coarse	Less than 18% Clay and more than 65% sand
2	Medium	Less than 35% clay and more than 15% sand; more than 18% clay if the sand content exceeds 65%
3	Medium Fine	Less than 35% clay and less than 15% sand
4	Fine	between 35% and 60% clay
5	Very Fine	More than 60% clay
9	Organic	
0	No texture	

Table 2. Inherent susceptibility to compaction according to texture and packing density

		Packing density t m^{-3}		
		Low	**Medium**	**High**
Texture Code	**Texture Class**	< 1.40	1.40 – 1.75	> 1.75
1	Coarse	VH	H	M[1]
2	Medium	H	M	M
3	Medium fine	M(H)	M	L[3]
4	Fine	M[2]	L[4]	L[3]
5	Very fine	M[2]	L[4]	L[3]
9	Organic	VH	H	

Susceptibility classes: L low; M moderate, H high, VH very high

[1] *except for naturally compacted or cemented coarse (sandy) materials that have very low (L) susceptibility.*

[2] *these packing densities are usually found only in recent alluvial soils with bulk densities of 0.8 to 1.0 t m^{-3} or in topsoils with >5% organic carbon.*

[3] *these soils are already compact.*

[4] *Fluvisols in these categories have moderate susceptibility*

Table 3. Vulnerability to compaction according to soil susceptibility and climate

Class	**Climate Zone**	**Perhumid**	**Humid A**	**Humid B**	**Sub-humid**	**Dry**
	Subsoil Moisture state	*Usually wet, always moist*	*Often wet, usually moist, rarely dry*	*Usually moist, seasonally dry*	*Seasonally moist and dry*	Mostly dry
Soil	**PSMD mm**	**≤ 50**	**51 – 125**	**126 – 200**	**201 – 300**	**> 300**
Susceptibility	**FC Days**	**> 250**	**150 – 250**	**100 – 149**	**< 100**	**≤ 40**
VH		E[1] (E)[2]	E (E)	V (E)	V (V)	M
H		V (E)	V (E)	M (V)	M (M)	N
M		V (E)	M (V)	N (M)	N (N)	N
L		M (V)	N (M)	N (N)	N (N)	N

Classes of vulnerability to compaction:
N not particularly vulnerable; M moderately vulnerable; V very vulnerable, E extremely vulnerable
Moisture states are defined in Hodgson (1997) as: Wet <1 kPa, moist 1-1500 kPa, dry >1500kPa
[1] Classes outside brackets refer to situations with firm topsoil conditions.
[2] Classes within brackets refer to situations with loose/weak topsoil conditions.
PSMD potential soil moisture deficit (Jones and Thomasson, 1985).
FC Days Duration of field capacity, measured in days (Jones 1985, Jones and Thomasson, 1985).

Table 4. Vulnerability to subsoil compaction for a range of British soils.

UK Soil Series	WRB Group[1]	Subsoil Texture Class	Clay Content (wt%)	Subsoil Bulk Density t/m^3	Subsoil Packing Density t/m^3	Subsoil Suscepti-bility Class	Vulner. Class FC[2] (firm)	Vulner. Class PWP[3] (firm)
Naburn	Haplic Arenosol	Coarse	6	1.23	1.32	VH	E	V
Newport	Haplic Arenosol	Coarse	5	1.43	1.47	H	V	M
Wisbech	Calcaric Fluvisol	Medium	6	1.35	1.40	M	V	N
Wick	Eutric Cambisol	Medium	11	1.36	1.46	M	V	N
Romney	Calcaric Fluvisol	Medium Fine	15	1.33	1.47	M	V	N
Agney	Eutri-gleyic Fluvisol	Medium Fine	30	1.32	1.59	M	V	N
Hanslope	Calcari-stagnic Cambisol	Fine	35	1.43	1.83	L	M	N
Fladbury	Eutri-gleyic Fluvisol	Very Fine	45	1.04	1.67	H	M	L
Evesham	Calcari-stagnic Cambisol	Very Fine	60	1.41	1.92	L	M	N

[1] WRB World Reference Base (FAO et al. 1998)
[2] FC Field Capacity (5kPa)
[3] PWP Permanent Wilting Point (1500kPa)

Table 5. Simplified classification of vulnerability to subsoil compaction.

Broad Class for cartographic purposes	Vulnerability class on basis of soil and climate
Not vulnerable (N)	Not particularly vulnerable
Vulnerable (V)	Moderately vulnerable
Vulnerable (V)	Very vulnerable
Vulnerable (V)	Extremely vulnerable

Table 6. Climate, land management, cropping and loading trends

Climate Zone	Land Use Description	Machinery Loads Timeliness, Soil moisture	Response
Perhumid PSMD <50mm FC >250 days	Mainly extensive grazing Forestry Amenity	Rarely heavy traffic [except for forest harvesting] Mainly high moisture contents	Increasing Loads → Increasing strength →
Humid A PSMD 51-125mm FC 150-250 days	Mostly intensive grazing Some rotational arable farming Forestry	Forage harvesting Winter feed transport Disposal of animal wastes from indoor feeding Often high moisture contents	
Humid B PSMD 126-200mm FC 100-149 days	Often continuous arable monocultures Some rotational grass Permanent grass on small farms Intensive arable systems	Much heavy machinery for tillage and harvesting Most landwork during spring and autumn when moisture contents are high Moderate moisture deficits allow regeneration and corrective loosening	
Sub-humid PSMD 201-300mm FC <100 days	Mainly intensive arable farming in northern Europe with root crops, vegetables and irrigation on larger farms	Much heavy machinery for tillage, harvesting and crop protection Landwork may be continuous throughout the year Strong moisture deficits	
Dry PSMD >300mm FC ≤ 40 days	Viticulture and horticulture with extensive irrigation in Mediterranean zone	Compaction linked to erosion under intensive rain in the Mediterranean zone Compared to the rest of Europe these areas are dry	

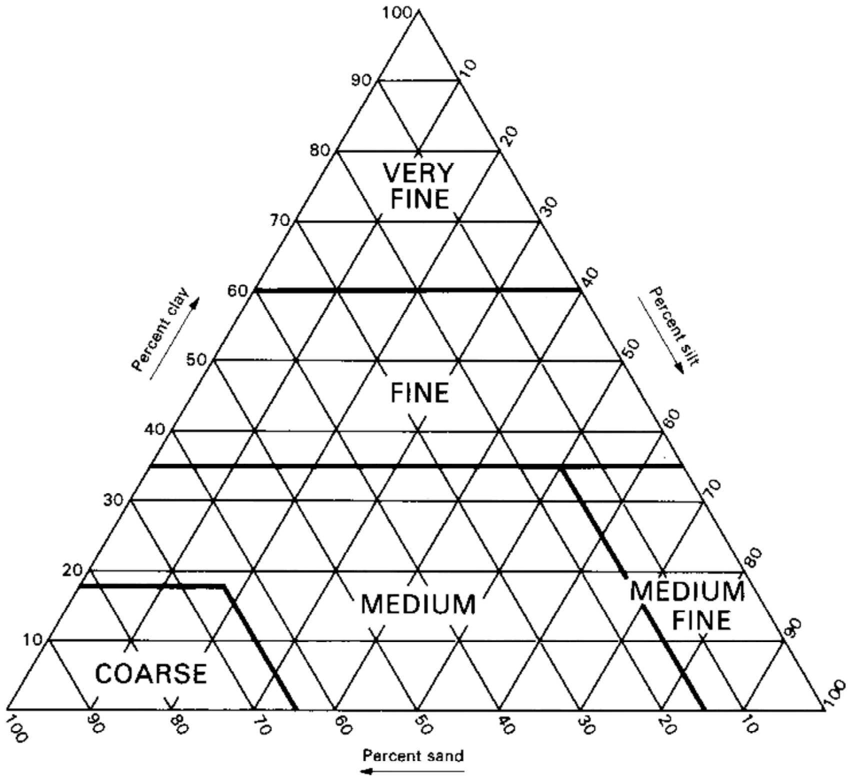

Figure 1 Texture classes of FAO used in the European Soil Database

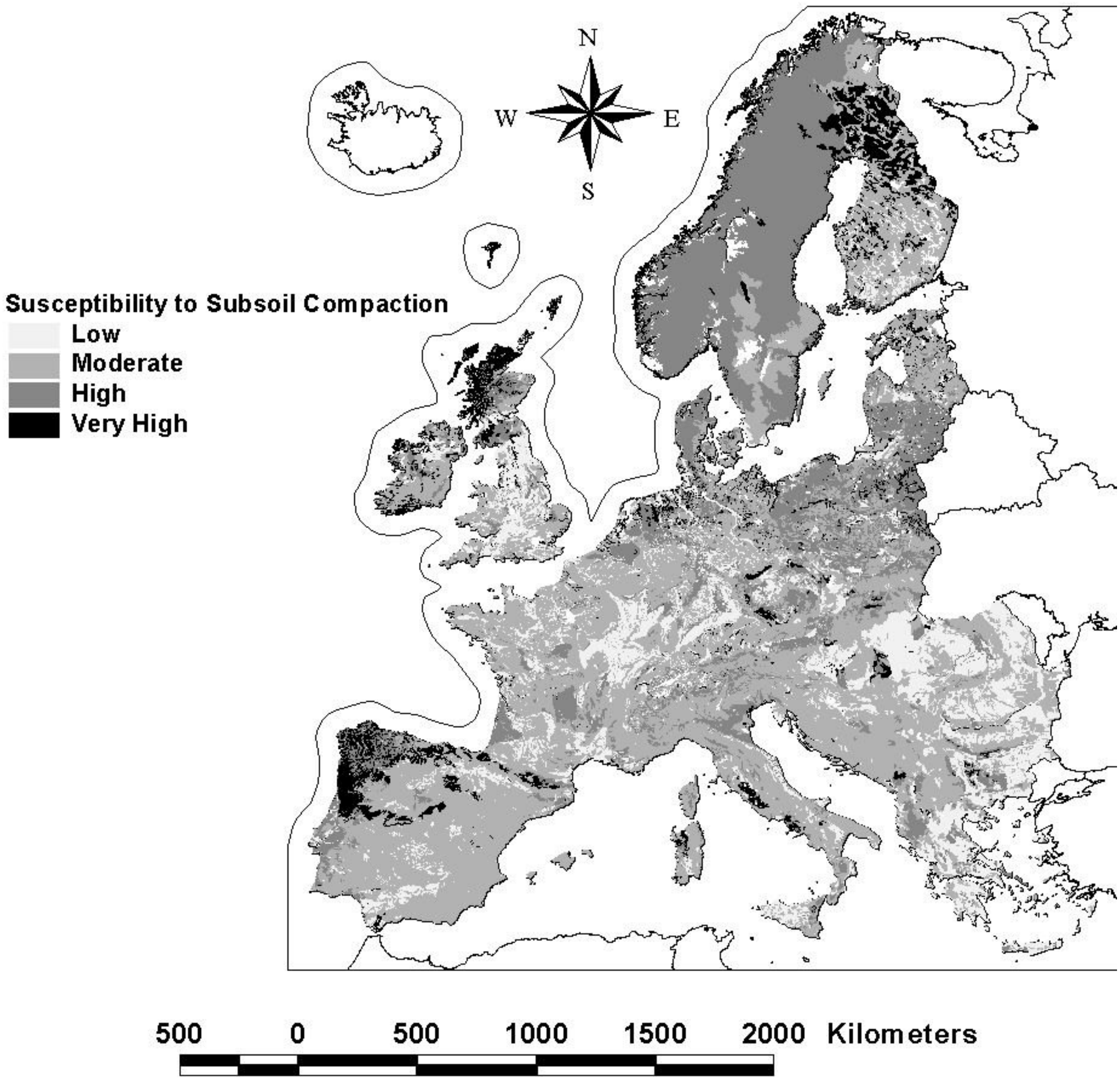

Figure 2 Provisional map of inherent susceptibility of subsoils in Europe to compaction,
based on soil properties alone. [Note: Further input data are required on climate and land use before vulnerability to compaction of subsoils in Europe can be inferred from the susceptibilities shown here.]