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Toward a tool aimed to quantify soil compaction risks at a regional scale: Application to Wallonia (Belgium)

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ABSTRACT

The spatial analysis of the soil compaction risk has been developed at the regional level and applied to Wallonia (Belgium). The methodology is based on the estimation of the probability of exceeding the preconsolidation stress due to the application of loads on the soil.

Preconsolidation stresses (Pc) are computed from the pedotransfer functions of Horn and Fleige (2003) at pF 1.8 and 2.5 and classified into 6 categories ranging from very low Pc (<30 kPa) to extremely high Pc (>150 kPa). The computation requires the knowledge of pedological (texture, organic content), mechanical (bulk density, cohesion, internal friction angle), and hydraulic variables (water content available, non-available water content, air capacity, saturated hydraulic conductivity). These variables are obtained from databases like HYPRES or AARDEWERK or from pedotransfer functions. The computation of Pc takes into account the spatial structure of the data: in some cases, data are abundant (e.g., texture data) and spatial variability is taken into account through geostatistical methods. In other cases, the data is sparse but uncertainty information can be extracted from the knowledge of the statistical distribution. Maps of the most probable Pc class are produced. Uncertainty is computed as the classification error probability. Implementation of these methods in Wallonia showed that Pc values higher than 120 kPa are reached either on 64% of the territory at pF 2.5 or on 55% at pF 1.8. A higher uncertainty was found at pF 2.5 than at pF 1.8. Uncertainty was also found higher for clay and clayed loess than for other textural classes present in Wallonia.

The risk of compaction is defined as the probability that Pc is exceeded by the stress created by a load applied to the soil at a depth of 40 cm, the loads being similar to those induced by agricultural or forestry tires. It appeared that subsoil compaction risks exist mainly in loamy forest soils with small coarse fragments supporting loads similar to that existing on logging machines.

In the zones where the uncertainty is low, the developed tool could be used as a basis for providing policy measures in order to promote soil-friendly farming and forest practices.

1. Introduction

Compaction concerns agricultural and forestry crops and results from the passage of heavy machines on sensitive soils, mainly during harvest operations and harvest transport. The detrimental effects of soil compaction on the crop production have been reported in many studies on both agricultural and forest soils (Hakansson and Reeder, 1994; Hamza and Anderson, 2005; Greacen and Sands, 1980; Goutal, 2012). Compaction causes a decrease in porosity and an increase in soil strength that may restrict root growth and affect the density and diversity of soil mesofauna and bacterial communities (Soane and van Ouwerkerk, 1995; Batey and McKenzie, 2006; Frey et al., 2009; Lipiec et al., 2012). Soil compaction not only reduces crop and forest production, but has also negative environmental effects (Jones et al., 2003). Indeed, saturated hydraulic conductivity is reduced, increasing the risk of runoff of water and pollutants toward surface waters, and the movement of nitrate and pesticides into ground waters. The volume of soil available to act as a buffer for pollutants is reduced. The risk of soil erosion increases through the presence of excess water above compacted layers. Because of the reduction of soil aeration, production of greenhouse gases through denitrification may occur by anaerobic processes (Jarvis, 2007; Hoefer, 2010).

Considering the detrimental effects of soil compaction, the proposal of the EU Commission for a Soil Framework Directive mentions soil compaction as one of the major threats to a sustained

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quality of soils in Europe (COM, 2006). The compaction of the subsoil, defined as ‘subsurface soil material that lies below the normal cultivation depth or pedological A horizon’, is particularly problematic since it is difficult and expensive to alleviate (Hakansson and Reeder, 1994; Spoor et al., 2003). Subsoil compaction risks are increasing with growth in farm size, increased mechanisation and equipment size, and the drive for greater productivity (Jones et al., 2003).

In analysing soil compaction, a distinction has to be made between the susceptibility of soils to compaction and their vulnerability. Susceptibility is the likelihood that compaction occurs if subjected to factors that are known to cause compaction (Louwagie et al., 2009). Susceptibility to compaction depends on quasi-permanent characteristics such as texture and carbon content and on short-term changing characteristics such as soil moisture condition. It ranges from sand (least susceptible) – loamy sand – sandy loam – loam – clayed loam – loamy clay to clay soils (Woods et al., 1944, cited by Louwagie et al., 2009). Medium- and fine-textured loam and clay soils are resistant to mechanical pressure at low water contents but they are highly susceptible to severe compaction at high water contents (Horn et al., 1995).

The soil’s vulnerability to a given threat is determined taking into account the inherent soil susceptibility and an exposure estimate based on an evaluation of the stresses inflicted by land management and climate (Troldborg et al., 2013). Jones et al. (2003) propose a simple classification system for subsoil vulnerability to compaction 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, such as soil texture, nature of clay, bulk density, organic matter content, structure, soil moisture content and soil moisture potential. Second, the susceptibility class is converted into a vulnerability class through consideration of the likely soil moisture status at the time of critical loadings. The authors conclude that some improvements could be brought to the method, including namely the use of pedotransfer functions. Another method for estimating the soil’s vulnerability or the risks of soils being further compacted is obtained by comparing calculated soil strengths with vertical stresses created by a given wheel. The soil strength is usually expressed by the precompression stresses evaluated from pedotransfer functions (Van den Akker, 2004; Horn and Fleige, 2003). More recently, Troldborg et al. (2013) developed Bayesian belief networks for assessing the risk of soil compaction, allowing the combination of available data from standard soil surveys and land use databases with qualitative expert knowledge.

In order to face the challenge of the Soil Framework Directive, if implemented, the Governments of the European Union wish to identify areas of risk and develop relevant policy measures suited to provide soil-friendly farming practices. The report of the SoCo (Sustainable Agriculture and Soil Conservation) project presents a European map of natural soil susceptibility to compaction (Louwagie et al., 2009). Based on soil properties, it gives an idea of the geographic spread of compaction susceptibility. Unfortunately, this map does not provide sufficiently accurate information to determine the extent of actual and potential problems at a Regional Scale and to bring responses to the regions in Europe who have been asked to develop environmental plans.

In Wallonia (South of Belgium), political discussion on the problem of compaction is namely taken into account by the Walloon Forest Code which is in application since 13th September 2008 (Décret relatif au Code forestier wallon, 2008) and prohibits explicitly damages on the ground that could have long-term consequences on the forests vitality. Wallonia occupies around 17,000 km^2. Forest areas represent 530,600 ha while agricultural areas represent 756,000 ha. Forest soils are mainly Cambisols, while agricultural soils are mainly Luvisols.

The aim of the paper is thus to develop a methodology that would be suitable to help the policy-makers in order to limit soil compaction. The methodology concerns the subsoil (40 cm depth) because compaction in this horizon is generally considered as particularly serious because of its persistence. As far as possible, the methodology should involve the use of existing databases. The main challenge concerns the structure of the information. In some cases, the information is abundant while in other cases, there is a lack of data. At the same time, the uncertainties relative to the data and to the modelling process have to be taken into account and their contributions in terms of overall uncertainty on the results have to be quantified.

2. Material and methods

The methodology comprises two stages. Firstly, the susceptibility of soils to compaction is assessed by computing the soil strength, this latter being expressed by the precompression stress (Pc). Secondly, the vulnerability of soils is analysed by computing the vertical stresses created in the soils by a load similar to that applied by a wheel and comparing it to the precompression stress.

2.1. Soils susceptibility

Soil compaction is conveniently defined by the precompression stress (Pc): loading of a soil will cause compaction only if a certain level of stress called ‘precompression stress’ is exceeded (Dexter, 1988; Lebert and Horn, 1991; Horn et al., 1994). When soil is

Table 1
Pedotransfer functions to calculate the precompression stress for different soil textures at pF 1.8 and 2.5 (Horn and Fleige, 2003).

	Textural classes	Symbol	Pedotransfer function	r^2
1	Sand	S	$Pc_{1.8} = 438.10(x1) - 0.0008(x8_{1.8})^3 - 3.14\,(x4) - 0.11(x3_{1.8})^2 - 465.60$ $Pc_{2.5} = 410.75(x1) - 0.0007(x8_{2.5})^3 - 3.41\,(x4) - 0.35(x3_{2.5})^2 - 384.71$	0.778 0.710
2	Sandy loess	LS	$Pc_{1.8} = 169.30(x1) - 29.03(x6)^{0.5} + 6.45(x5) + 32.18\ \log(x7_{1.8}) - 9.44\,(x8)_{1.8} + 27.25\ \sin(x4) + 119.74\ \log\,(x3_{1.8}) + 19.51$ $Pc_{2.5} = 89.50(x1) - 23.99\,(x6)^{0.5} - 2.89\,(x5) + 125.76\ \log(x7_{2.5}) - 1.14\,(x\,8)_{2.5} + 26.90\ \sin(x4) - 51.46\ \log(x3_{2.5}) - 77.25$	0.828 0.874
3	Loess	L	$Pc_{1.8} = 374.15(x1) - 4.10(x6) + 3.38(x2)_{1.8} - 1.58(x5)^{-0.5} + 1.79(x7)_{1.8} + 1.09(x4) - 6.37(x8_{1.8})^{0.67} + 0.088(x3_{1.8})^2 - 472.77$ $Pc_{2.5} = 460.71(x1) - 20.33(x6) + 9.08(x2)_{2.5} - 2.38(x5)^{-0.5} + 2.86(x7)_{2.5} + 4.50(x4) - 20.96(x8_{2.5})^{0.67} + 0.304(x3_{2.5})$ $^2 - 610.62$	0.765 0.847
4	Clay (<35%) and clayed loess	ALA1	$\text{Log}(Pc_{1.8}) = 0.843 - 0.544(x5)^{0.33} - 0.022(x4) + 7.03(x7_{1.8})^{-1} + 0.024(x8)_{1.8} - 0.015(x3)_{1.8} + 0.725$ $\text{Log}(Pc_{2.5}) = 0.844(x1) - 0.456(x5)^{0.33} - 0.026(x4) + 12.88(x7_{2.5})^{-1} + 0.003(x8)_{2.5} - 0.016(x3)_{2.5} + 1.419$	0.808 0.804
5	Clay (≥35%) and clayed loess	ALA2	$Pc_{1.8} = 4.59(x1) - 1.02(x6) - 16.43(x5)^{0.33} + 0.31(x4) - 1.57(x3)_{1.8} + 3.55(x7)_{1.8} + 1.18\,(x8)_{1.8} - 18.03$ $Pc_{2.5} = 70.65(x1) - 0.55(x6) - 7.01(x5)^{0.33} + 1.32(x4) - 1.08(x3)_{2.5} + 1.72\,(x7)_{2.5} + 1.05(x8)_{2.5} - 100.94$	0.774 0.763

$X1 = \gamma_d$: bulk density (g/cm^3); $X2 = c_a$: air capacity (v/v ; %); $X3 = \theta_a$: available water (v/v ; %); $X4 = \theta_{na}$: non available water (v/v ; %); $X5 = K_s$: saturated hydraulic conductivity (cm s^{-1}) $X6$ = MO: total organic content (g/g ; %); $X7$ = c: cohesion (kPa); $X8$ = Ø: internal friction angle (degrees); Pc: precompression stress, pF 1.8 or 2.5 (kPa).