Machine Weight and Soil Compaction:

TASC V2.0.xls – a Practical Tool for Decision-Making in Farming

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Abstract

TASC (TYRES/TRACKS AND SOIL COMPACTION) is an Excel application that permits rapid evaluation of the risks of severe soil-compaction damage in the subsoil by taking into account both soil characteristics and machine load. Texture, hardness, maximum depth of loosening, tyre dimensions (width and diameter), wheel load and inflation pressure are the key parameters on which the application is based. In addition to this, a georeferenced statement of soil and loading characteristics allows us to create a 3D map of the risks of severe soil-compaction damage. The final purpose of this is the acquisition and processing of data during the actual harvest; incorporating an alarm in the monitoring system would allow farmers to intervene by emptying their hoppers before the critical load point is reached. A first example by ploughing with uninterrupted registration of the dynamic load and of the traction of the wheel estimated with sensor-tyre is presented here.

Key Words: prevention of soil compaction, 3D map of compaction damage risk, TASC

1. Introduction

During the past three to four decades the weight of agricultural and forestry machinery has quadrupled. Much-vaunted advances in technology, aimed at increasing both production and productivity, have often been at the expense of safeguarding soil structure. Sporadic ponding water, erosion and soil compaction observed in all of the major mechanised agricultural zones in Europe and elsewhere attest to this. The complex combination of higher immediate profit with lower environmental damage has lead to a technology which allows site-specific management, through which the machine and the soil properties are considered according their variability in time and space (Duboisset et al. 2008). A knowledge of the temporal variability of the dynamic load, especially during harvesting, or the spatial variability of soil properties like texture, of penetration resistance or maximum tilling depth for a defined time is, therefore, essential for mapping and delineating compartmental zones on the field to prevent severe soil damage. The objectives of the present paper are to present i) the TASC tool which permits evaluation of the risk of soil compaction in the subsoil according to soil and machinery load properties and ii) coupled with georeferenced data acquired with sensor-tyre (Cemagref patent n° 05-11455), to present an additional application of the tool to evaluate the spatial variability of the risk of severe compaction damage. Possibilities and limits are briefly discussed.

2. Theoretical basis of TASC

2.1. Principle of TASC

With regard to the danger to the soil from compaction damage, TASC uses the basic concept of precompression stress. If the stress F exceeds the precompression stress R of a particular soil, the soil tends to react plastically and deforms. If the precompression stress R is not exceeded, no plastic deformation takes place and the soil tends to react elastically. In this case, the soil structure does not fundamentally change as a result of loading (Fig. 1).

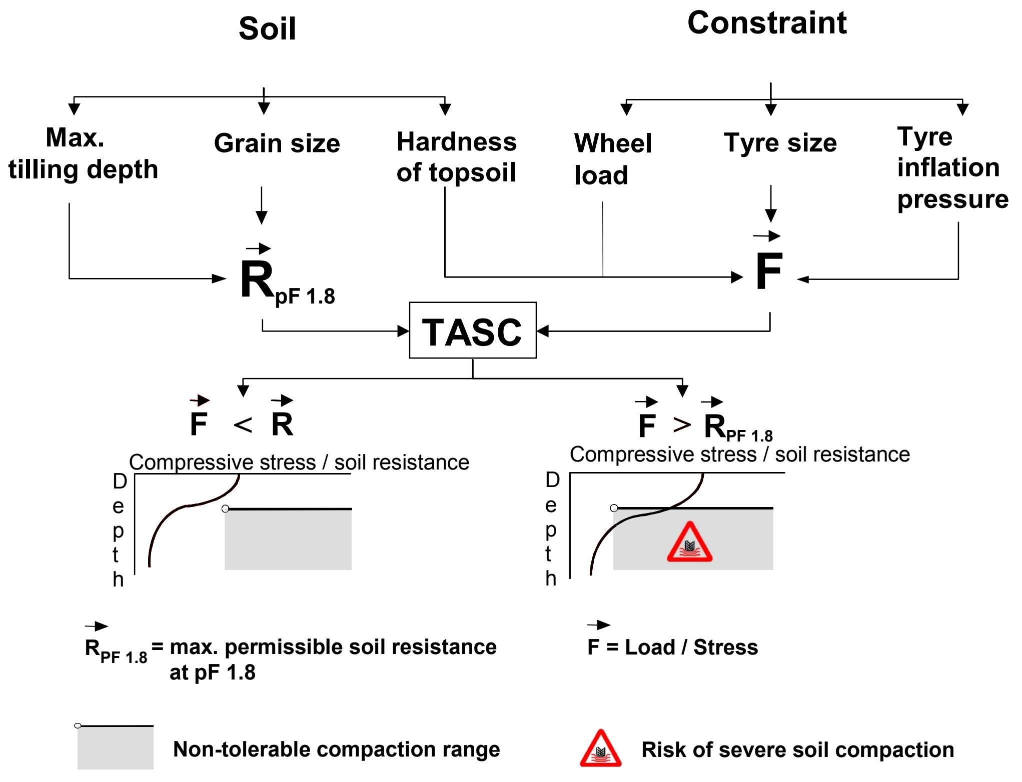

Fig. 1. TASC application evaluation principle

TASC calculates the stress propagation from soil and load input data, and assesses the compaction damage risk for a pF value of 1.8. Measurements in compacted subsoil have shown that stress propagation does not alter significantly with increasing water content in the partly saturated area (Diserens and Steinmann. 2002). The TASC flow diagram is given in appendix A.

2.2. Pressure propagation at depth and top soil stability

Stress propagation in the soil can be calculated using the basic algorithm for two-dimensional representation of isobars in isotropic soil from Boussinesq's formula (Fröhlich. 1934) (Eq. 1) with correction factors q according to topsoil consistency (Bastgen and Diserens. 2009).

$$\sigma_z = \frac{2q\sigma_m}{\pi}\left[\arctan\frac{ab}{Rz} + \frac{abz}{R}\left(\frac{1}{a^2+z^2} + \frac{1}{b^2+z^2}\right)\right] \quad \text{with} \quad R^2 = a^2 + b^2 + z^2 \qquad \text{Eq. 1}$$

where: σ_z (Pa): vertical stress at depth z,

σ_m (Pa): mean contact pressure,

σ_0 (Pa): equivalent contact pressure,

z (m): depth,

a, b (m): length and width of contact area (equivalent rectangle),

q: factor for the stability of tilled soil or ratio σ_0/σ_m

As the penetration resistance increases, the q value and the equivalent contact pressure both decrease. The q value at the experimental sites lies in a range between 0.11 minimum for very hard topsoil and 2.81 for very soft topsoil directly after ploughing and harrowing (Fig. 2).

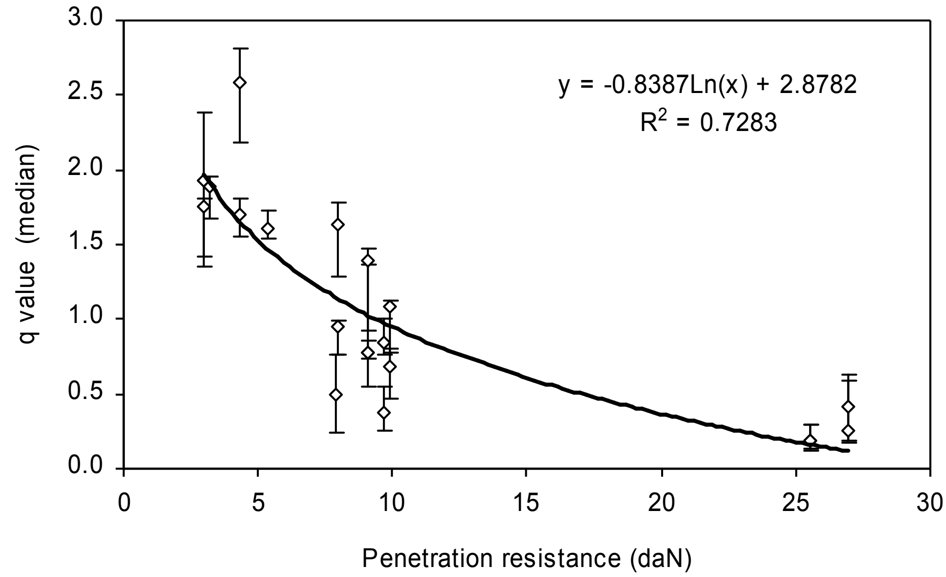

Fig. 2. q value (median) as a function of penetration resistance for mineral soils (Bastgen and Diserens. 2009)

The softer the soil, the less the stresses are propagated horizontally, the greater the contact pressure and the more intensively the compressive stresses will penetrate down into the soil. The penetration resistance or topsoil hardness determines the intensity of stress propagation with regard to the soil bearing capacity. It is determined using penetrometers with a screwdriver head. TASC V2.0 calculates the pressure distribution for three categories of topsoil stability (firm, semi-firm and soft) or for individual penetration resistance values (Table 1).

Table 1. Topsoil stability classes, corresponding penetration resistance PR and q values for the calculation of pressure propagation (Diserens. 2010)

Topsoil stability	PR range [daN]	PR reference for calculation [daN]	q value for calculation
soft	< 5	4.0	1.73
semi-firm	5 < 8	7.0	1.26
firm	≥ 8	12.0	0.81

2.3. Preconsolidation and stability point limit

The standard value for effective density of 1.7 Mg/m^3 according to the Swiss Pedology Society is used as a reference value by TASC (BGS Dokument. 2004). This parameter is a function of the clay content (Eq. 2):

$$D_{eff.}\ (Mg/m^3) = D_s\ [Mg/m^3] + 0.009\ [C\%] \qquad \text{(Eq. 2)}$$

where: D_{eff} is the effective density, D_s is the bulk density, C is the clay content (gravimetric)

Table 2. Equivalent precompression stress values (σ_p) (pF 1.8) for the standard value for effective density 1.7 (D_{eff} in g/cm^3) depending on clay (C in %) and silt (Si in %) content

Soil texture	According to Lebert data record (1989)	According to Qasem data record (2000)	**TASC**
	$\log \sigma_p =$ $0.534 + 0.912\ D_{eff} - 0.006C$ R = 0.6453	$\log \sigma_p =$ $0.811 + 0.627\ D_{eff} - 0.0036C + 0.003\ Si$ R = 0.6498	
Loamy clay, clay			
41-77% C 22-48% Si	min 49.8 max 69.8	min 61.8 **max 78.3**	**80**
Clayey, loamy, sandy silt, silt			
9-42% C 52-86% Si	min 68.9 **max 107.6**	min 83.7 max 105.9	**105**
Clayey loam, loam			
21-40% C 29-37% Si	min 70.1 max 89.1	min 74.1 **max 85.1**	**85**
Sandy loam, loamy sand			
11-20% C 18-39% Si	min 94.0 **max 104.8**	- -	**105**
Loamy sand, silty sand, sand			
1-9% C 3-22% Si	min 107.6 **max 119.9**	- -	**120**

According to Qasem et al. (2000), bulk density correlates most closely with precompression stress. In order to calculate the maximum permissible soil resistance (equivalent precompression stress or values corresponding to an effective density of 1.7 Mg/m^3 for different soils) regressions between the effective density and the precompression stress at pF 1.8 were calculated from two data records (Table 2). The highest value for each particular size class was selected and must therefore be taken with due seriousness.

3. Testing of the model

Altogether 73 out of 93 situations were validated from 15 locations to check the TASC application (Diserens 2010). In the remaining 20 cases the soil was excessively compacted prior to vehicle movement, in twelve of them between 35-40 cm (Tab. 3). There was no unforeseen severe compaction, either in the topsoil or subsoil.
With a deduction of 0.1 g/cm^3 for the topsoil as proposed by Petelkau (1991) (standard value for topsoil 1.6 instead of 1.7 g/cm^3), the agreement for topsoil increases to nearly 80%. Severe compaction occurs more rapidly. The number of "severe soil compaction" deficiency messages decreases. If soil type is characterised by entering clay and silt content, the stability limit is reduced. Checking is carried out more rigorously and hence with more

Table 3: Validation of the TASC application with field measurements – (subsoil: water tension Θ < 63 hPa in 98 % of situations) – Four cases: hardness parameterisation through classes or values (kg) – type of soil parameterisation through classes or values (clay content %, silt content %)

	Topsoil 10-15 cm		Subsoil 35-40	Subsoil 55-60	Mean for soil		Mean for subsoil
Standard value [g/cm^3]	1.7	1.6*	1.7	1.7	1.7	1.6*	1.7
Measurements total	33	33	35	25	93	93	60
Case 1 – Topsoil hardness$_{value}$ / Type of soil$_{class}$							
Total valid situations	30	24	23	20	73	67	43
Agreement in %	63.3	79.2	82.6	100	79.5	86.6	90.7
Case 2 - Topsoil hardness$_{class}$ / Type of soil$_{class}$							
Total valid situations	30	24	23	20	73	67	43
Agreement in %	63.3	79.2	78.3	100	78.1	85.1	88.4
Case 3 - Topsoil hardness$_{value}$ / Type of soil$_{value}$							
Total valid situations	30	24	23	20	73	67	43
Agreement in %	53.3	79.2	73.9	100	72.6	83.6	86.0
Case 4 - Topsoil hardness$_{class}$ / Type of soil$_{value}$							
Total valid situations	30	24	23	20	73	67	43
Agreement in %	56.7	79.2	60.9	100	69.9	79.1	79.1

* Standard value of the effective density for the topsoil 1.6 g/cm^3 after deduction according to Petelkau (1991).

certainty. Severe compaction messages appear sooner, without the soil becoming seriously deformed. In the subsoil (35-40 cm) the best results were found in case 4 (values given for soil stability and category details for soil type). Agreement of 83% was observed between 35-40 cm. If the values from the deeper layer are also taken into consideration (55-60 cm), agreement then increased to over 90%.

According to our measurements, the gradient of severity by predicting the risk of compaction damage increased gradually from the case 1 to the case 4.

4. A TASC application with georeferencied load data (case of furrow road by ploughing)

4.1. Methods

Site and soil data are shown in Table 4. For the moisture and penetration resistance the field area was divided in twelve sections, four bands from west to east where each band was subdivided into three parts, north, center and south. The stability point limit with TASC (Fig. 1) is fixed at pF 1.8 (field capacity) but the water potential during the measurements is higher (drier), therefore minimizing the risk of severe soil compaction damage.
The soil parameters for calculation of the vertical stress propagation under the rear wheel are, firstly, the class of soil texture (loamy sand) and the class of soil hardness (firm), and secondly the clay content (8.6%) and the value distribution of the penetration resistance in the twelve sectors of the field. In the second case the evaluation will be stronger due to the decrease of the stability point limit from 120 to 108 kPa.

Table 4: Position and soil characteristics (loamy sand, firm) of the site

Site	Commune	Varennes s/Allier (F)	Surface (ha)	4.5
	Longitude / Latitude	3º 20' 35 E / 46º 25' 75 N	Crop	Stubble winter wheat
Soil at 25 cm depth	Loamy sand			
	Clay (%)	8.6	Sand fine (%)	19.5
	Silt (%)	11.9	Sand coarse (%)	61.6
	Stability point limit$_{pF8\text{-}class}$ (kPa)	120	Humidity$_{(grav\%)}$	9.0* ± 0.7
	Stability point limit$_{pF8\text{-}value}$ (kPa)	108	Penet. resist.** (kPa)	17.2* ± 2.2

* mean with standard deviation, ** penetration resistance

Load characteristics are shown in Table 5. Basis data for the determination of dynamic load and traction force were recorded with a sensor-tyre equipped with linear transducers measuring the vertical, longitudinal and radial deformation of the tyre (x, y and z axis). Dynamic load and traction force were then deduced by trilateration calculation (Chanet et al. 2009). The worst case with the highest load (rear wheel in the furrow at 25 cm soil depth) will only be considered here for the prediction of risk.

Table 5: Tractor and plough characteristics

Tractor	Renault 120-54, 80 kW	
Plough	IH – 4-plough shear, reversible	
Tyres front / rear	14.9 R 28 BIB’XM18 / 16.9 R 38 BIB’XM18	
Inflation pressure (kPa)	140	
Static load front / rear (daN)	990	1,410
	Rear wheel in the furrow	Rear wheel out of the furrow
Dynamic load (daN)	2,279* ± 209	1,915* ± 296
Traction (daN)	1,980* ± 273 daN	1,413* ± 236 daN

* mean with standard deviation

4.2. Results and discussion

Penetration resistance varied between 12 daN in the northern part and 20 daN the south-eastern part of the field. With all values above 8 daN at 25 cm depth, the soil can be considered as firm. Independently of the soil, the characteristics of the charge with the distribution of the dynamic load by constant inflation pressure is shown in figure 3. With no constant inflation pressure, the dynamic contact pressure would be more representative than the dynamic load alone to characterize the charge properties. The mean value of the dynamic load did not exceed 2,500 daN. Only in one sector (south west) were values above 3,000 daN recorded.

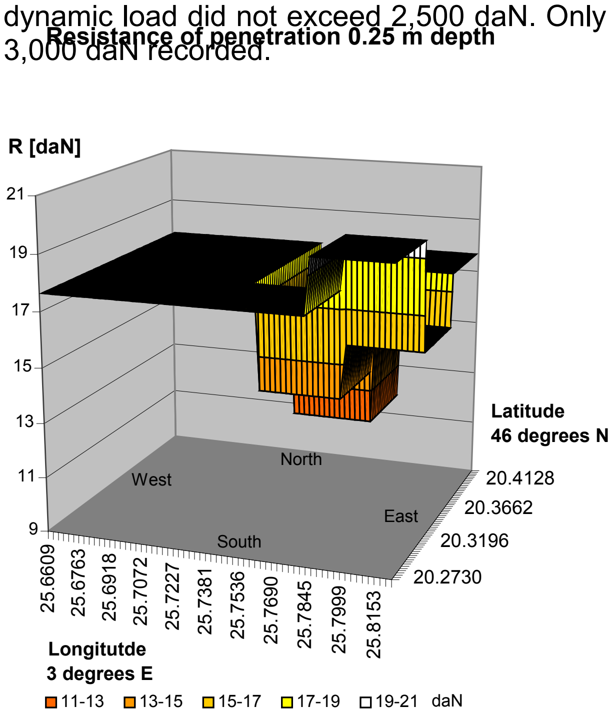

Fig. 3. Distribution of penetration resistance R at 25 cm soil depth for the testing field

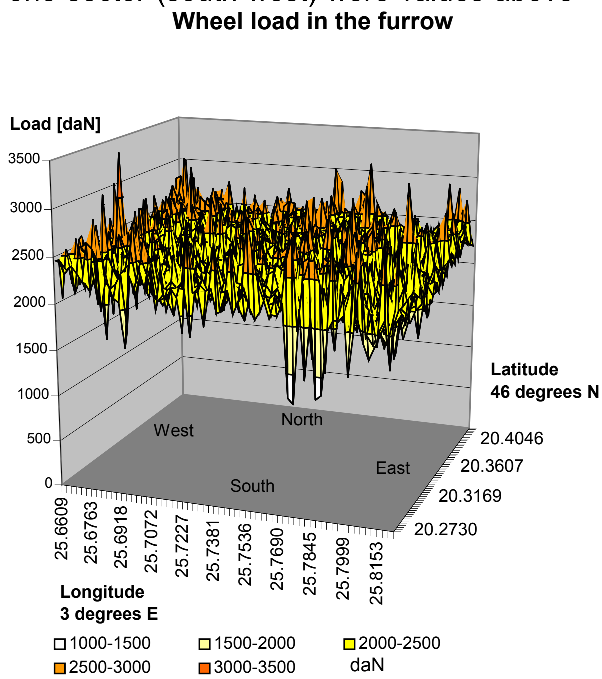

Fig. 4. Distribution of dynamic load in the furrow at 25 cm soil depth

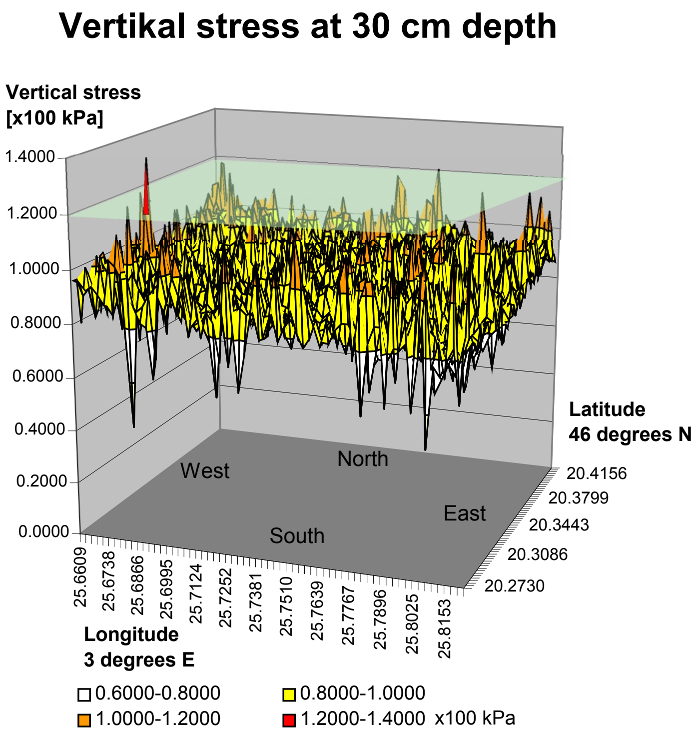

Fig. 5. 3D map of compaction damage risk. Vertical stress for a homogeneous firm soil with a stability point limit of 120 kPa for a loamy sand at 30 cm soil depth

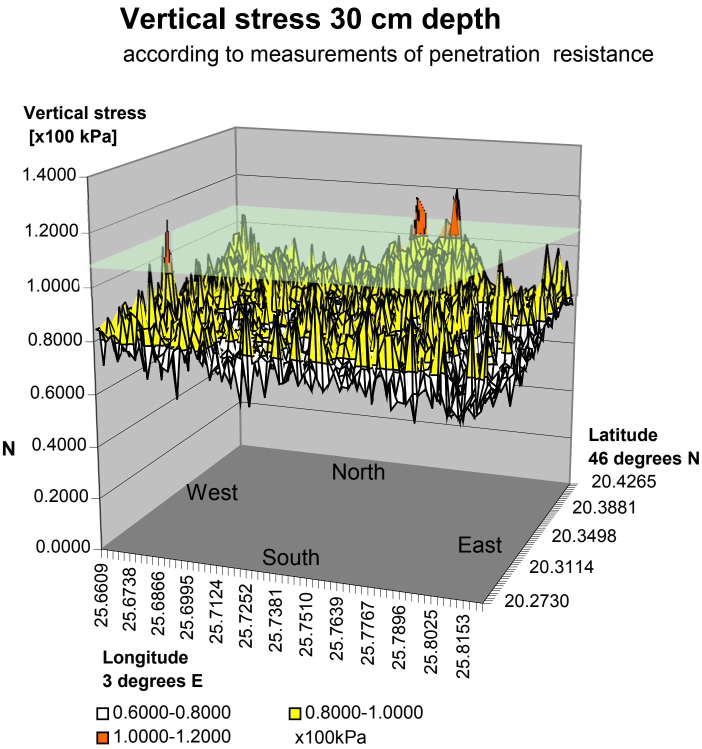

Fig. 6. 3D map of compaction damage risk. Vertical stress according to the distribution of penetration resis-tance values with a stability point limit of 108 kPa by 8.6% clay content at 30 cm soil depth

In a first evaluation (fig. 5), the TASC application calculated the soil damage risk with a pre-defined penetration resistance value of 12 daN (firm soil) and with a stability point limit of 120 kPa for loamy sand (Tables 2 & 4). Because of the higher values of measured soil hardness, the vertical stress seems to be overestimated, but compensated for on other hand by a higher soil stability limit. Considering the clay content and the spatial variation of the penetration resistance, the second evaluation in figure 6 revealed two sectors of risk, one in the south western part due to a particularly high load, and the second in the north eastern coupled with the effect of high load and lower soil consistency. In figure 6, because of the higher penetration resistance values, the predicted vertical stress is lower without generally exceeding 100 kPa.

To check the prediction of compaction damage risk, soil sampling with measurements of the effective density including clay content value (Eq. 2) at the corresponding depth would be necessary. For two reasons we can assume here that the risk of severe compaction is very low: i) the vertical stress at 30 cm depth does not exceed 120 kPa after taking the distribution of penetration resistance into consideration, and ii) the prediction tool is based on a pF value from 1.8 although the soil is obviously drier and consequently less sensitive.

Many studies propose solutions for assessing the space distribution of physical-mechanical soil properties like soil penetration resistance (Bölenius et al. 2006) or particle size distribution by means of electrical conductivity (Hinck S. et al. 2006). A future challenge will be to equip heavy self-propelled harvesters with well adapted instrumentation to also take soil properties into account. With the intention of effectively preventing soil compaction damage, should it not be necessary to check soil sensitivity shortly before harvesting? In this way it would be possible to organize the harvest by fixing beforehand the maximum load and the frequency of unloading according to the spatial distribution of soil properties like texture, penetration resistance and soil moisture.

5. Conclusions

The particular requirements of this first study are i) also to take into consideration the validation of risk with additional soil sample analysis, then allowing an optimal selection of the type of evaluation according to values or classes of soil properties, ii) to consider also the stability point limit under dry soil conditions (pF 2.5) for the prediction of risks. The TASC tool coupled with georeferenced load data recorded from farming and soil characteristics collected shortly prior to driving allows new perspectives in precision farming and soil protection.

6. References

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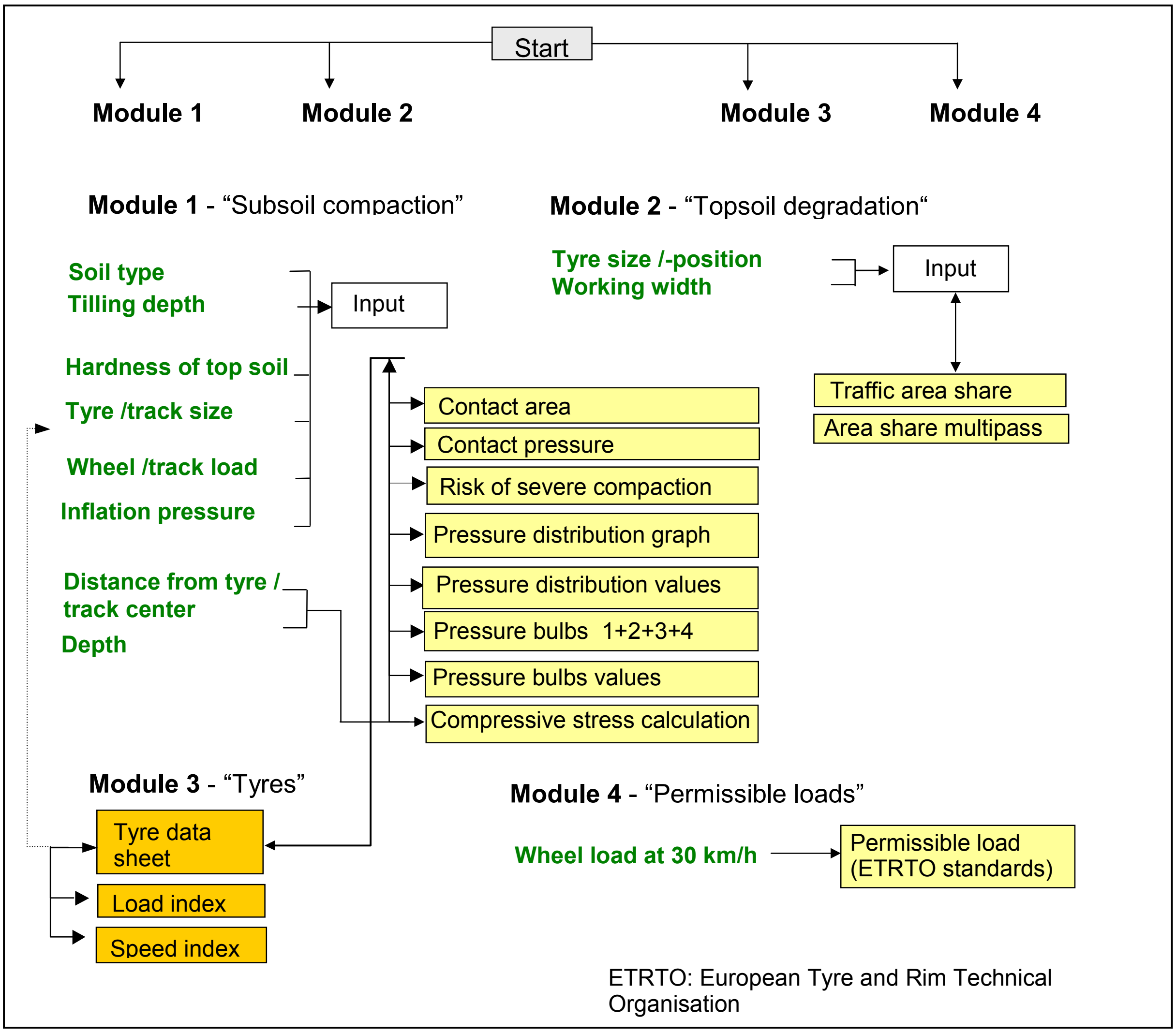
Appendix A



TASC flow diagram