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Soil Compaction, Soil Shearing and Fuel Consumption: TASC V3.0 – A Practical Tool for Decision-Making in Farming

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Abstract

Much vaunted advances in technology, aimed at increasing both production and productivity, have been at the expense of safeguarding soil structure. Soil compaction, soil shearing, ultimately erosion and sporadic standing water, observed in all of the major mechanized agricultural zones in Europe and elsewhere, attest to this. TASC (TYRES/TRACKS AND SOIL COMPACTION) is a validated Excel application consisting of five modules. The first one permits evaluation of the risks of severe soil compaction damage by taking into account soil characteristics and machine load. The evaluation is based on the pressure propagation – pre-compression stress concept. The second module simulates the traction force - slip curve providing also the limit beyond which top soil failure occurs. The evaluation of the soil failure risk is based on the ratio of soil shear stress to soil strength concept. Traction and fuel consumption can be determined for different soil conditions, tractor and tillage equipment. The third module calculates the share of trafficked areas, with a breakdown into single or multiple transits. A fourth module provides access to the technical data for more than 1,270 agricultural and forestry tyres. A fifth and final module related to road safety provides information on the maximum authorized loads, bearing in mind tyre type, inflation pressure and speed.

Keywords: Soil damage, traction force, fuel consumption

1. Introduction

Since the mid-1980s agricultural mechanization in Western Europe has increased substantially in the wake of technical progress and rationalization. The performance of agricultural machinery was enhanced dramatically, and the weight of implements, machinery and tractors rose significantly in parallel. With wheel loads of up to 5 tons for tractors, 11 tons for combine harvesters and 60 tons for sugar beet harvesters, soil is subjected to very heavy loads. Soil compaction is insidious, often long-lasting damage which is manifested in extreme weather conditions (persistent rain, drought, prolonged cold spells). Reduced yields of between 5 and 15 % can be observed (Heinonen et al. 2002). The problem here is not only soil compaction, but also topsoil cutting and deformation during traction work, as well as the issue of multiple transits. Topsoil cutting occurs when slip is high. This produces a loose, easily eroded layer (Battiato et al. 2013). Beneath this the soil is compacted and there is further shear. The resultant loosening is exacerbated during a multipass. Compaction and cutting lead to reduced water infiltration, which tends to increase the frequency and severity of flooding and erosion. Inappropriate equipment (tyres) or settings (tyre inflation pressure, speed), particularly during traction work, also result in excessive fuel consumption (Battiato & Diserens, 2013). Risks to the soil in the form of severe soil compaction damage, topsoil cutting and excessive energy consumption can be predicted using TASC. This practical tool (TASCV3.0) is presented here.

2. Model description

TASC V3.0 is the third version of a practical decision-making tool consisting of five modules [Fig. 1]. It lends itself to areas facing the problem of chassis-induced soil stress such as agriculture and forestry practice, consultancy, planning, teaching, administration, engineering companies, as the tyre, agricultural and forestry machinery industry.

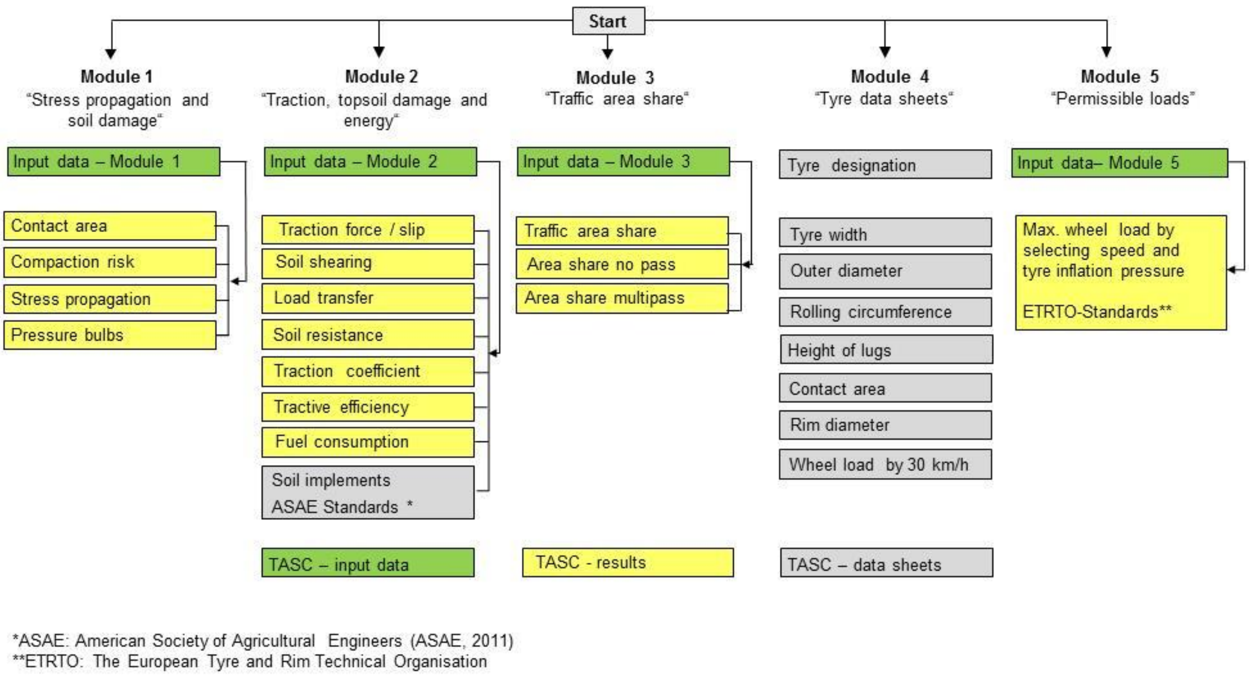

Figure 1: TASC results including tyre data sheets – an overview.

3. Basic principles when evaluating soil risks and energy requirement

3.1 Risk to subsoil caused by severe soil compaction damage

Soil deformation occurs as soon as an external force exceeds the corresponding soil reaction force. No deformation occurs if the compressive stress F according to Boussinesq (Eq. 1) (Lang & Huder, 1982) caused by a load impact at a particular depth of soil is less than the soil resistance R (also known as pre-compression stress).

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

Where σ_z = normal stress at the depth z
σ_m = mean contact pressure
q = concentration factor of the soil, depending on the hardness of the topsoil
a = horizontal coordinate of the contact area (x-direction)
b = horizontal coordinate of the contact area (y-direction)
z = corresponding soil depth

By low loads, the soil reacts elastically without any deformation. The soil reacts plastically, however, if F is greater than R. Deformation in the form of compaction may be expected (Fig.

2). This compaction is known as severe soil compaction damage if it occurs above a tolerated threshold at a depth of soil where loosening by conventional tillage equipment is no longer possible. The guideline value of effective bulk density (Eq. 2) is an important reference figure when evaluating the degree of compaction:

$$BD_{eff} = BD_d + 0.009\,C \qquad \text{Eq. 2}$$

where BD_{eff} = effective bulk density
BD_d = dry bulk density
C = clay content (gravimetric)

1.7 g/cm^3 is the indicative value for agricultural soil (Buchter et al. 2004). To calculate the maximum permissible soil resistance or compressive stresses, regressions between the effective bulk density and the pre-compression stress at pF 1.8 (soil moist and drained) and at pF 2.5 (soil dry) (Lebert, 1989) are formed from existing data sets. These were divided into five grain size categories: (1) loamy clay (2) clayey, loamy, sandy silt, silt (3) clayey loam, loam (4) sandy loam, loam-rich sand (5) loamy sand, silty sand, sand.

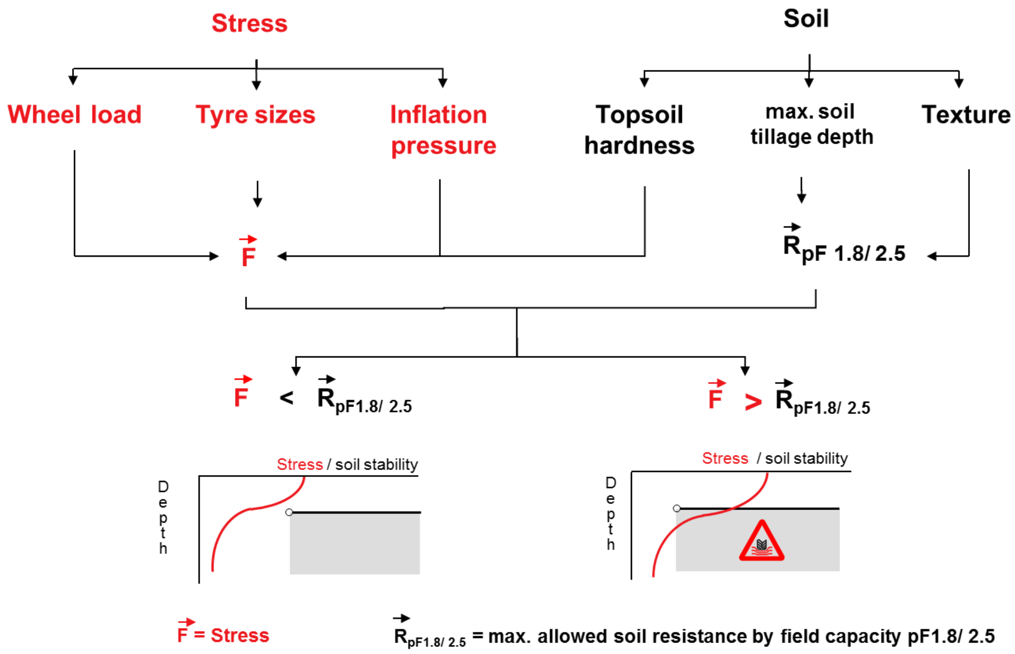

Figure 2: Module "Stress propagation and severe soil compaction damage" - evaluation principle.

3.2 Risk to topsoil caused by shear and motorised traffic

The interaction of tyre and soil during traction work triggers an interplay of normal and tangential forces [6]. Since soil shear strength τ_{max} increases as compressive stress σ increases, it is a function of compressive stress, soil cohesion and the angle of internal friction φ according to Mohr-Coulomb (Eq. 3) [5]:

$$\tau_{max} = (c + \sigma \tan\varphi) \qquad \text{Eq. 3}$$

where τ_{max} = soil strength
σ = normal stress at soil-tyre contact
c = soil cohesion
φ = angle of soil shear resistance (angle of internal friction)

Many agricultural soils show an elastic perfectly plastic behaviour with hardening, this implies that if the soil proves resistant to shear forces τ, $\tau < \tau_{max}$, then it behaves elastically or within its elasto-plastic domain. No splitting and limited shearing of the topsoil occurs. If, however, the shear stress τ reaches the soil strength τ_{max}, $\tau = \tau_{max}$, as traction and slip increase, then the soil behaves plastically; the soil breaks accumulating a great shear deformation (Fig. 3).

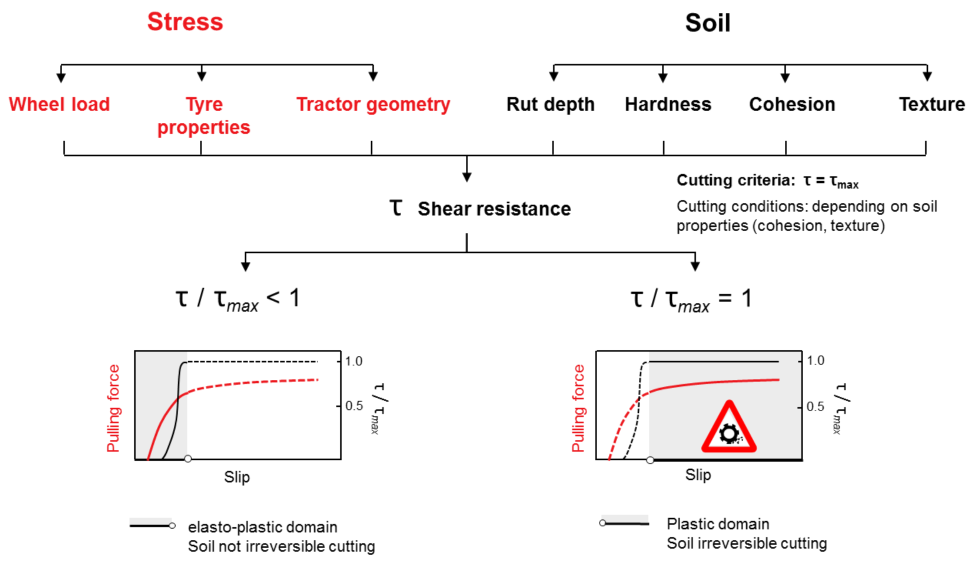

Figure 3: Module "Traction, topsoil damage" – evaluation principle.

The area share of the ruts is a further index of topsoil vulnerability. To maintain a high water infiltration on sensitively structured, moist, clayey or silty soils of low permeability it makes sense to restrict traffic to an area as small as possible. Coarse-grained sandy soils react less sensitively. The area share of the ruts can be calculated subject to work, tyre width and chassis configuration.

3.3 Checking soil risk using field tests before driving on the field

In practice it should be possible to check the trafficability of one's soil in respect of the risk of severe soil compaction damage and shearing with the minimum of time and effort and at no cost. We outline below four field tests for the characterisation of soil prior to using wheeled traffic.

Feel test: The feel test is used to determine soil grain size, which can be broken down into five classes. Soil moisture can also be assessed by the feel test. These two soil characteristics are important when ascertaining the stability point in limit range R (Module 1, Fig. 2) and the shear parameter φ (Module 2, Eq. 3) (Diserens & Battiato, 2013).

Double meters test: This determines the maximum loosening depth (critical soil depth) below which it is imperative to protect the soil from excessive compressive stresses σ_z (Module 1). In the first instance the modulus of deformation K can be calculated by ascertaining the rut depth, hence also the contact area, the circumferential force at the wheels and finally the traction in the case of drive wheel tyres (Module 2) (Diserens & Battiato, 2013; Battiato, 2012).

Screwdriver test: This makes use of a conventional screwdriver (no. 4 – tip 6 mm wide, 1 mm thick). Depending on the hand position the soil is classified as soft, semi-hard or hard. This test assesses both the q-value as a measurement of soil resistance (Eq. 1) shortly before it is driven over (Module 1) and the modulus of shear deformation k as a measurement characterising the shear resistance of the soil (Diserens & Battiato, 2013; Battiato, 2012).

Hoe test: This also employs a conventional implement. Penetration depth, handle height and body posture depending on the traction needed to cut the ground with the hoe are the input variables used to determine soil cohesion *c* as an additional shear parameter (Module 2, Eq. 3) (Diserens & Battiato, 2013).

Soil vulnerability based on soil conditions can only be reliably evaluated if the soil is effectively checked shortly before being driven over.

3.4 Simulation of energy requirement

Fuel consumption has a direct correlation to the power on the wheels, and is directly dependent on engine speed and torque. As engine speed rises the power increases at a specific torque. In modern tractors with power boost, however, the maximum power is less than the rated speed. The minimum specific consumption b_{eM} [g/kWh] takes place at an energy utilisation of approx. 80 % and a speed of approx. 70 % of the rated speed (Landis & Schiess, 2006).

The reference values selected were taken from the standardised ISO 8178C1 measurement cycle. These measured points focus on the torque and are weighted differently (Landis & Schiess, 2006). In the simulation model tractors are divided into two different rating classes (Schäffler & Keller, 2008).

For tractors with ratings ≤ 75 kW the specific fuel consumption is b_{eM} 248 g/kWh and for more powerful tractors (> 75 kW) it is 223 g/kWh.

The engine power P_M can be determined using the power on the wheels P_{GT} (Battiato, 2012) calculated from Module 2 and the efficiency factor η_G (Eq. 4):

$$P_M = \frac{P_{GT}}{\eta_G} \qquad \text{Eq. 4}$$

For engine transmission, be it for a manual or Vario gearbox, several authors suggest an efficiency factor η_G of 0.85 at high engine load (Kutzbach, 1989; Queitsch et al. 1984). The hourly fuel consumption B_e can then be calculated as follows (Eq. 5):

$$B_e = P_M \cdot \frac{b_{eM}}{1000} \cdot \frac{1}{\delta_D} \qquad \text{Eq. 5}$$

where B_e = hourly fuel consumption
P_M = engine power
b_{eM} = specific diesel consumption at the engine
δ_D = specific gravity of the diesel

The draft requirement depending on tillage equipment and soil properties can be calculated according to the ASAE standards (ASAE, 2011). Therefore, after considering the driving speed together with the specifics torques on the driving wheels, the energy need with the corresponding fuel consumption are simulated according to Diserens and Battiato (2013).

4. Validation

In the first module, ”Soil propagation and soil damage”, at the prompt “Severe soil compaction risk, no/yes” (25 cm and deeper) an agreement of 93 % was noted compared with measurements for the subsoil. In the case of topsoil the agreement was lower, between 54 and 62 %. In not one single case from a total of 207 cases checked was the message “no risk of severe soil compaction damage” displayed if the soil was shown to be excessively compacted during measurement. The evaluation therefore tends to be on the safe side (Diserens & Battiato, 2013).

Soil failed as soon as its strength was reached, exhibiting a rise in topsoil shear displacements (Fig. 4). This phenomenon was observed not only for one but for several tractor configurations with different weights and inflation pressures (Diserens & Battiato, 2013; Battiato, 2012). The ratio τ/τ_{max} of 0.99 seems to be an indicative limit, suitable for the practice. Beyond the corresponding slip threshold, the soil breaks. This limit depends on soil and tyre properties such as soil cohesion, angle of internal friction, respectively dimension, rolling radius, wheel load, inflation pressure, and stiffness.

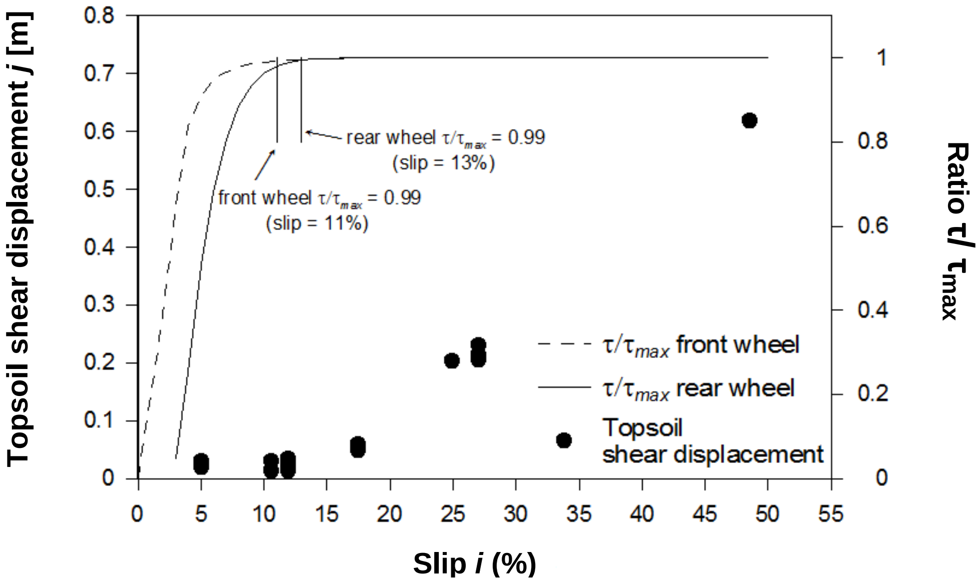

Figure 4: Evolution ot topsoil shear displacement compared with the simulated evolution ot the maximum ratio τ/τ_{max} with wheel slip for the front and the rear wheel. Tractor power 65 kW, tractor weight 40.0 kN, tyre inflation pressure 60 kPa.

The calculated fuel consumption figures from reference values for specific diesel consumption at the engine are highly consistent with the values obtained in independent field measurements with three different tractors [9] (Fig. 5).

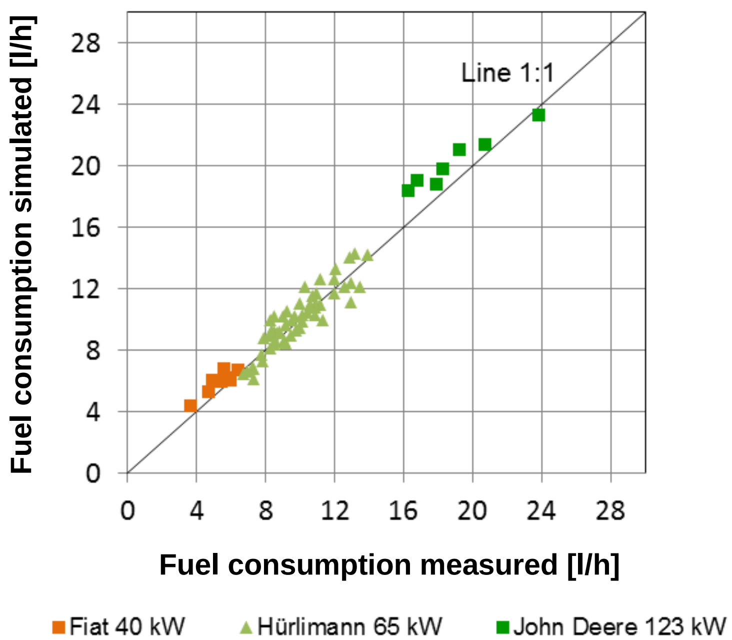

Figure 5: Comparison between measured and simulated fuel consumption per hour for three tractors with different powers.

5. Conclusions

The risk to soil, whether in the form of severe soil compaction damage or topsoil cutting, can be reliably checked for a broad spectrum of wheeled agricultural machinery, implements and soils. This means that the appropriate mechanisation and soil management can be used to safeguard soil fertility in the long term. Fuel consumption can also be simulated for standard methods of mechanised soil tillage, and savings made by employing optimisation measures. As yet TASC cannot the assess the risk to organic soils or carry out slip, traction or energy calculations for tracked vehicles.

6. Acknowledgements

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7. References

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Tool Specification

Version	TASC V3.0. 2013
Operating system	Win Office 2007 or higher/ Mac OSX 10.8.2 or higher
Software	Office Excel 2007 or higher/ Excel 2011 Mac or higher
Languages	German, French, English
Memory requirement	Excel 14.5 MB – Manual pdf 1.8 MB
Issued by	Agroscope, 8356 Ettenhausen, Switzerland
Orders	www.agrartechnik-agroscope.ch or bestellung@agroscope,admin.ch Phone: ++41 58 480 31 31
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