About Terranimo®

1. **What is Terranimo® and what does it do?**
Terranimo is a computer model that predicts the risk of soil compaction by farm machinery. Terranimo is primarily addressed to farmers, agricultural contractors and consultants, and enforcement authorities. The simulation model calculates the risk of compaction damage for real operating conditions. The results can serve to optimise the use of agricultural machines, and thus help to avoid damage to the soil structure.

2. **The people behind Terranimo®**
Terranimo is the work of an international team, formed around Swiss and Danish scientists. In Switzerland, these are Thomas Keller from the ART Agricultural Research Station in Reckenholz and Matthias Stettler from the School of Agricultural, Forest and Food Sciences HAFL. In Denmark, the work is carried out by Per Schjønning, Mathieu Lamandé and Poul Lassen from the Department of Agroecology of Aarhus University at the Research Centre Foulum in Tjele.

3. **The idea behind Terranimo®**
Terranimo is based on a simple and well known principle: the pressure exerted by an agricultural machine (soil stress) is balanced by the resistance of the soil (soil strength, fig. 1).

![Figure 1: Terranimo is based on the principle of the balance between soil stress and soil strength.](image)

If the soil strength is greater than the stress exerted, no permanent compaction will occur and no damage is to be expected. Conversely, if the soil strength is lower than the stress, subsoil compaction is unavoidable and one should refrain from driving on the soil.
Estimating soil stress and soil strength is not simple, however. Terranimo takes a number of important parameters into account in order to calculate the risk of soil compaction as precisely as possible. The model exists in two versions adapted to different users: Terranimo® light for a simple and quick assessment of the risk of soil compaction in standard situations, and Terranimo® expert for a detailed analyses of the risk of soil compaction under specific conditions.
4. Terranimo® light: risk assessment made easy

Terranimo light uses four parameters to quickly assess the risk of soil compaction: wheel load, tyre inflation pressure, soil moisture and soil clay content.

Wheel load and tyre inflation pressure are used to calculate the stress in the subsoil at a depth of 35 cm. This depth was chosen in reference to the prescriptions on soil protection applied in the Swiss building sector and is justified by the particular vulnerability of the subsoil, as compaction damage in this layer is very difficult to repair.

The formula for calculating the soil stress was derived from wheeling tests carried out in Denmark using various types of commercial tyres under different combinations of wheel load and tyre inflation pressure. The results obtained showed that wheel load and tyre inflation pressure describe the soil stress quite precisely, whatever the make and type of tyres used. This relation can be depicted in a nomogram (figure 2), showing how soil stress (represented as isolines) varies with higher wheel loads and greater tyre inflation pressures.

![Soil stress nomogram](image)

**Figure 2: Soil stress nomogram (modified from Schjønning et al. 2012).** The isolines show the stress at 35 cm depth as a function of wheel load and tyre inflation pressure.

Soil strength can be estimated using the water suction, a measure of soil moisture, and the clay content. The soil strength function was derived by laboratory soil compression tests (oedometer tests) carried out in Denmark on ca. 500 soil samples. The samples were tested at least 3 different water suctions (5, 10 and 30 cbar) and their clay content varied between 5 and 18%. The resulting nomogram (fig. 3) shows that the correlations are somewhat more complex than in the case of soil stress: the effect of water suction on soil strength varies, depending on the clay content of the soil. In moist conditions (water suction < 10 cbar), light soils (i.e. low clay contents) are in principle more stable than heavy soils. When they dry out however, their resistance increases much less than that of clayey soils. Around field capacity (water suction ≥ 10 cbar), the influence
of the clay content is relatively small. This rule was confirmed by oedometer tests carried out in Switzerland.

![Soil resistance nomogram](image)

**Figure 3:** Soil resistance nomogram (modified from Schjønning, unpublished). The isolines show precompression stress at 35 cm depth, as a function of clay content and water suction.

In Terranimo light, these values of soil stress and soil strength are recorded in a three-coloured decision chart (fig. 4). This constitutes the actual risk assessment. The effective compaction risk is assigned to one of three hazard levels, green, yellow or red.

Meaning of the colours:
- **Green**: no risk of soil compaction. Driving on the soil at its present moisture level and with the intended equipment will not damage the soil.
- **Yellow**: in the yellow area there is a considerable risk of soil compaction. Knowledge of additional soil properties allows to further specify the actual risk. For example, it will decrease in stony (> 10% stones in the subsoil), or well-structured soils (i.e. thanks to soil conservation measures, regular root distribution, high humus content or good lime supply). Stress should be reduced by all possible means (e.g. by lowering tyre pressure, only partially filling the hopper or installing twin tyres).
- **Red**: the red area in the chart shows the strength/stress combinations at which permanent compaction to the subsoil is to be expected. Refrain from driving on the soil unless you have taken appropriate measures to return to the yellow hazard level (e.g. reducing wheel load or tyre pressure).

The green-yellow limit corresponds to a stress equal to 50% of soil strength. According to current knowledge, this represents to the transition between elastic (reversible deformation, no permanent damage) and plastic (irreversible) deformation of the soil, i.e. permanent compaction (Keller et al. 2012). The yellow-red limit corresponds to a stress equal to 110% of soil strength. In the red
area, according to recent results of wheeling tests, considerable plastic deformations (and thus permanent, damageable, compaction) are to be expected.

![Decision chart](image)

Figure 4: The decision chart as presented in Terranimo® light, correlating soil stress and soil strength and classifying the compaction risk in three levels (green, yellow, red).

5. Terranimo® expert: a detailed analysis of the physical load applied to the soil

Terranimo expert is much more complex than Terranimo light and is intended as a tool for specialists to study specific situations of vehicles circulating on soil. Terranimo expert is composed of 4 sub-models:

1. Upper model boundary: contact area and stress distribution between the tyre and the soil
2. Stress propagation in the soil
3. Estimation of soil strength as a function of depth
4. Assessment of compaction risk based on the calculated stress and the actual soil strength

The upper model boundary was determined with the FRIDA model (Schjønning et al., 2008), which simulates the contact area and the stress distribution between tyre and soil. The tyre footprint is described by a super ellipse and the stress distribution by a combined exponential (perpendicular to the direction of movement) and power function (in the direction of movement). FRIDA describes the actual situation very well, in particular the predominant influence of tyre inflation pressure (fig. 5).
Figure 5: Diagrams of stress distribution between tyre and soil, as measured (left) and modelled with FRIDA (right), for two different tyre inflation pressures. Tyre used in this example: Michelin MultiBib 650/65R38 with 3.5 t wheel load.

In order to use FRIDA with other tyres than those studied, estimator functions were developed to calculate the various model parameters. Accordingly, it is possible to predict the tyre-soil contact area and stress distribution for all types of tyre, using easily obtainable tyre data (width, diameter, manufacturer recommended and effective inflation pressure), the wheel load and the condition of the topsoil.

In order to simplify the input of tyre data, a databank of commonly used tyres was added to the model. It now contains over 1000 tyres from a number of manufacturers (Alliance, Continental, Goodyear, Kléber, Michelin, Nokian, Trelleborg and Vredestein), listed with all their technical specifications according to ETRTO (European Tyre and Rim Technical Organisation).

Stress propagation is calculated analytically in Terranimo, based on the formulas of Boussinesq (1885), Fröhlich (1934) and Söhne (1953). An important element of this theory is the concentration factor \( v \), which determines the shape of the stress distribution in the soil (fig. 6).
Figure 6: Shape of the stress distribution for different concentration factors $v$.

In Terranimo expert, the factor $v$ varies according to soil strength, as already proposed by Söhne (1953): in wet soils, $v = 6$, in hard (dry soils), $v = 4$, and in moist soils $v = 5$.

In Terranimo expert, the soil strength is calculated in the same way as in the light version, and the corresponding compaction risk is also presented in the form of a three-coloured decision chart. In addition, Terranimo expert also produces diagrams of stress distribution at the tyre-soil interface and in the soil profile (onion charts). With this information it becomes possible to assess the compaction risk along the entire soil profile, and not only at 35 cm depth, as in Terranimo light.

References


