# An introduction to Terranimo®

## 1. How to use this note

Sections 2-5 give some general information about the Terranimo® decision support tool. Sections 6-10 provide a short introduction to the use of the tool. And finally, sections 11-13 give some explanation of the calculations taking place when using Terranimo®.

## 2. What is Terranimo® and what does it do?

Terranimo® (Terramechanical model) is a computer model that predicts the risk of soil compaction by farm machinery. The model estimates the risk of compaction for realistic operating conditions. It is designed to include the most recent knowledge on soil strength and stress from machinery. These stress and strength aspects are interacting in a complicated way. The results may thus be valuable for understanding the dynamics when arable soil is loaded with machinery. The knowledge gained may help identify the most beneficial traffic systems for sustainable farming. Terranimo® is continuously updated with the most recent results in soil compaction research. The tool is thus considered of interest for researchers and extension officers interacting with farmers. However, the simple design with default or easily modified machinery and soil conditions makes the tool useful also for farmers interested in reducing compaction of their soils. Terranimo® may help identify the 'weakest points' in some specific management system. The potential benefit of taking into use wider, low pressure tyres or machinery with more axles etc can be quantified. Also, the effect of soil moisture conditions on soil vulnerability to compaction can easily be displayed and may be an eye-opener to a better management of the fields. Terranimo® can be used free of charge. The creators of Terranimo® have no responsibility for potential unforeseen harm that might be caused through the use of Terranimo®.

## 3. The people behind Terranimo®

Terranimo® is the work of an international team formed around Swiss and Danish scientists. Per Schjønning and Mathieu Lamandé from Department of Agroecology at Aarhus University, Denmark, joined forces with Thomas Keller, ART Agricultural Research Station in Reckenholz, and Matthias Stettler, School of Agricultural, Forest and Food Sciences HAFL, both Switzerland, to combine the current knowledge on soil compaction in an interactive model. Poul Lassen in cooperation with Margit S. Jørgensen, both Aarhus University, designed and programmed the web tool.

## 4. Terranimo® International and other versions of the model

Terranimo® International is the common label for a range of national versions, including Terranimo® Global. All versions can be run in nine languages based on user's choice: English, German, French, Spanish, Dutch, Norwegian, Swedish, Finnish or Danish. For the time being, four national versions are available: Denmark, Norway, Finland, Switzerland. Model calculations are identical for all versions. They only deviate with respect to the default soil types, soil moisture conditions, and list of machinery that the user is met with when opening the specific version. In addition, Terranimo® Global offers a number of typical FAO soil types. Terranimo® International can be accessed through the web portal www.terranimo.dk. Technical aspects of the Terranimo® International model is described by Lassen et al. (2013).

The Swiss part of the Terranimo® founding group (Matthias Stettler and Thomas Keller) also has created a specific Terranimo® version for official regulation of field traffic by the Swiss authorities. This version deviates from Terranimo® International in miscellaneous ways.

## 5. The basic characteristics of Terranimo®

Terranimo® basically compares vertical stresses from wheels with soil strength. Decision support on the sustainability of intended field traffic is provided based on the comparison of stress and strength, which is done for all the soil profile (to 150 cm depth). Generally, stresses should not exceed soil strength. The present version of Terranimo® does not provide a quantitative estimate of soil deformation taking place when stress exceeds strength. Neither does the model estimate compaction effects on soil functions (including crop yields). The strength of the tool is thus primarily the possibility of evaluating the potential effects of wheel load, tyre type and inflation pressure, and soil moisture conditions on soil stresses and strength.

## 6. General aspects of the user interface

When starting Terranimo®, the user is met with four tabs,- two for inputs (machinery and soil) and two for outputs (stresses in the tyre-soil interface and stresses transmitted to the soil profile):

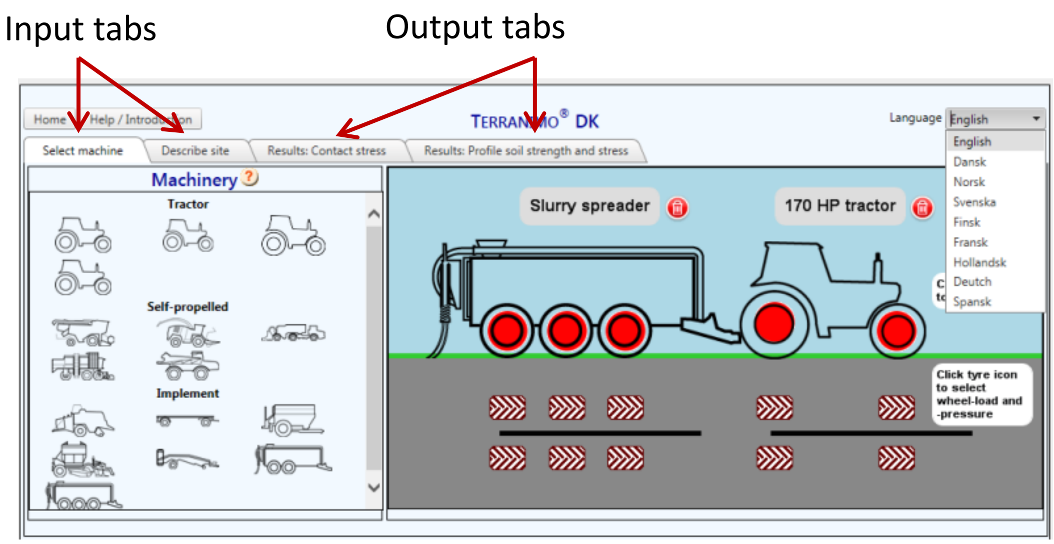



Figure 1. The opening window when starting up Terranimo®.

Terranimo® by default is set up with a version-specific soil type. The default moisture condition is field capacity, corresponding to a matric potential of -100 hPa (pF2). The model also provides a default machinery when opening the tool. The user may thus go directly to the output tabs and see the results of the pre-defined combinations of machinery and soil conditions. Afterwards or alternatively as a first step, the user may select other machines or change tyres on the machine axles. The wheel loads and tyre inflation pressures may be changed as well. Also, alternative soil types and moisture conditions can be chosen by selecting the ‘Describe site’ tab. The user then typically (re-)opens the results tabs for evaluation of the effects of the modifications.

## 7. Input: Select machine

The ‘Select machine’ tab provides a list of machinery that can be selected (Figure 1). Differently sized tractors can be merged with miscellaneous implements (slurry trailers, potato and beet harvesters, big baler etc). Terranimo® automatically takes care of the load transfer from trailers to the tractor axles. Alternatively, self-propelled machines like combine, beet harvester, forage harvester, pesticide sprayer and slurry spreader may be chosen. By clicking the tyre icon of the machine axles, a sub-menu allows for changing tyres, and for modifying wheel loads and inflation pressures.

## 8. Input: Describe site

The ‘Describe site’ tab allows for choosing soil type and soil moisture conditions. The left-hand part entitled ‘Soil texture’ presents the default soil type for the given version (country) in question. The textural composition of that soil is listed,- based on users choice either for all 15 layers of 10 cm increment or only for each horizon with identical texture (Figure 2). A drop-down menu ‘Select soil type’ allows for choosing among a range of soils typical for the specific country. The user may also manually type in the textural composition of his/her own soil (‘Manual texture’, Figure 2).

The ‘Texture from soil database’ is an option until further only active for Denmark. If ticking this facility, the window will be modified with options for first selecting location (by GoogleMaps) and later reading the soil data for that location in the Danish soil data base. Actually, an interpolation procedure is performed between observed soil values close to the selected location. This is to provide the best possible estimate of local texture.

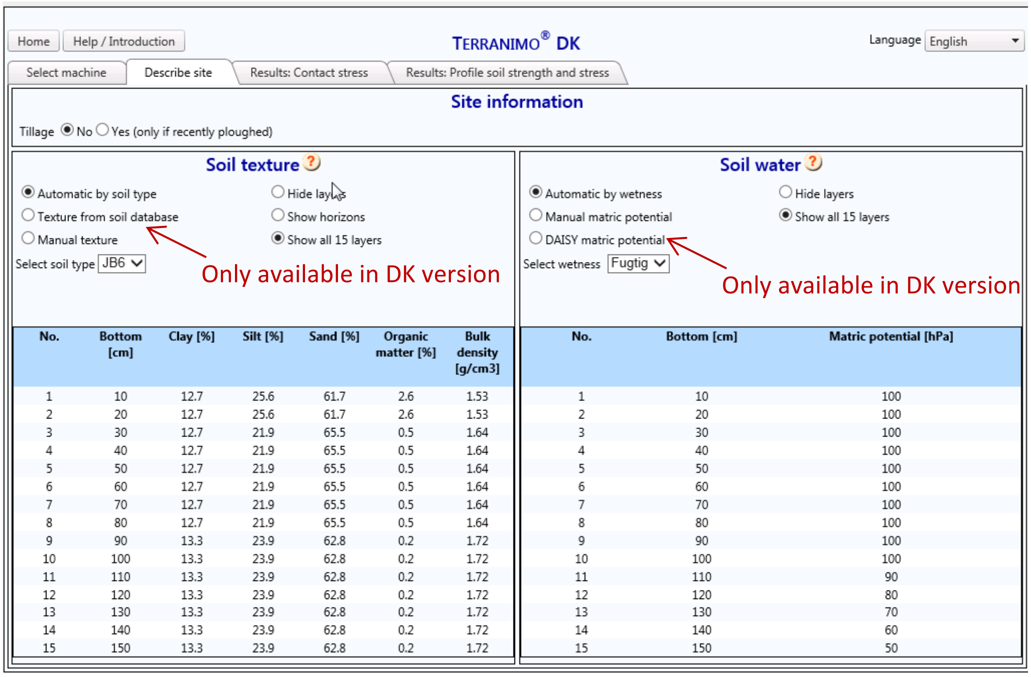



Figure 2. The user interface for input of soil texture and moisture conditions (tab ‘Describe site’).

The right-hand part of the 'Describe site' window is used for selecting the soil water conditions at which the simulation should be carried out. Soil strength and also stress transmission is dependent on the soil moisture conditions (see later sections for explanation of calculations). The user may choose among pre-defined moisture conditions ('Automatic by wetness'), Figure 2. 'Moist' corresponds to field capacity as found for example in the spring. In contrast, 'Wet' and 'Dry' should be selected in case traffic on winter-wet or medium dry summer situation should be simulated, respectively. Based on user's choice, the matric potentials of the 15 10 cm increment layers of the soil profile are displayed below the selection table (Figure 2). As for soil texture, users may manually input matric potentials in case these are known,- f.ex. from tensiometer readings ('Manual matric potential', Figure 2).

The 'DAISY matric potential' option is only active for Denmark. If activating this facility, again new options appear on the window. If location has not been chosen for soil texture input, the 'Select location' procedure should now be performed prior to activating the 'Calculate DAISY matric potential' button. Also the crop and the date for simulation should be chosen. After this, weather data are automatically read at weather stations close to the location selected, and estimates for the specific location obtained through interpolation as for soil data mentioned above. The soil matric potential is then calculated by the DAISY Soil-Plant-Atmosphere-Continuum model (Abrahamsen and Hansen, 2000).

## 9. Results: Contact stress

The 'Results: Contact stress' tab provides a graph of the stresses in the contact area for all tyres on the selected machinery. Figure 3 shows the situation for a tractor-trailer combination for slurry application. All trailer tyres are Nokian ELS tyres loaded with each ~60 kN (6 tonnes). Three different combinations of tyre dimension and inflation pressure are used here to indicate the potential in reducing the contact stress (Figure 3).

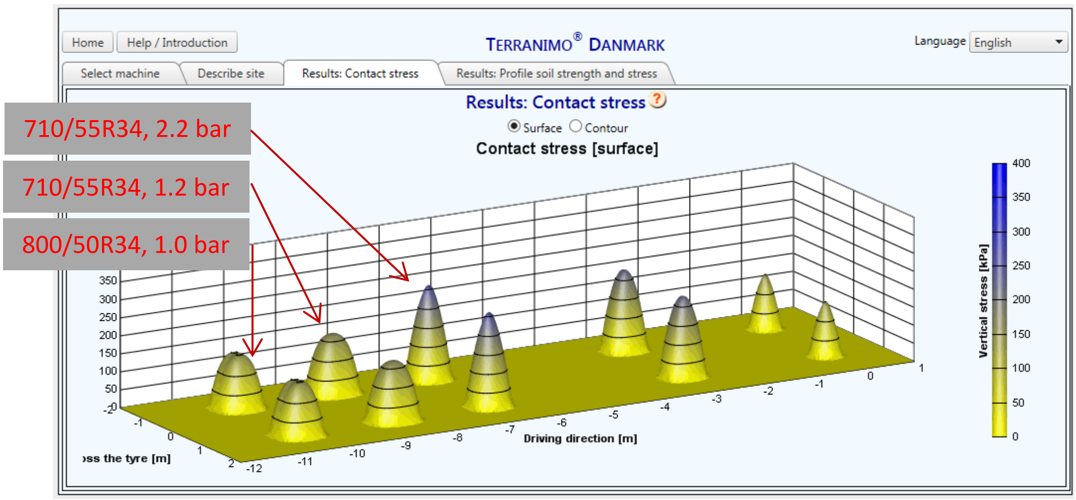
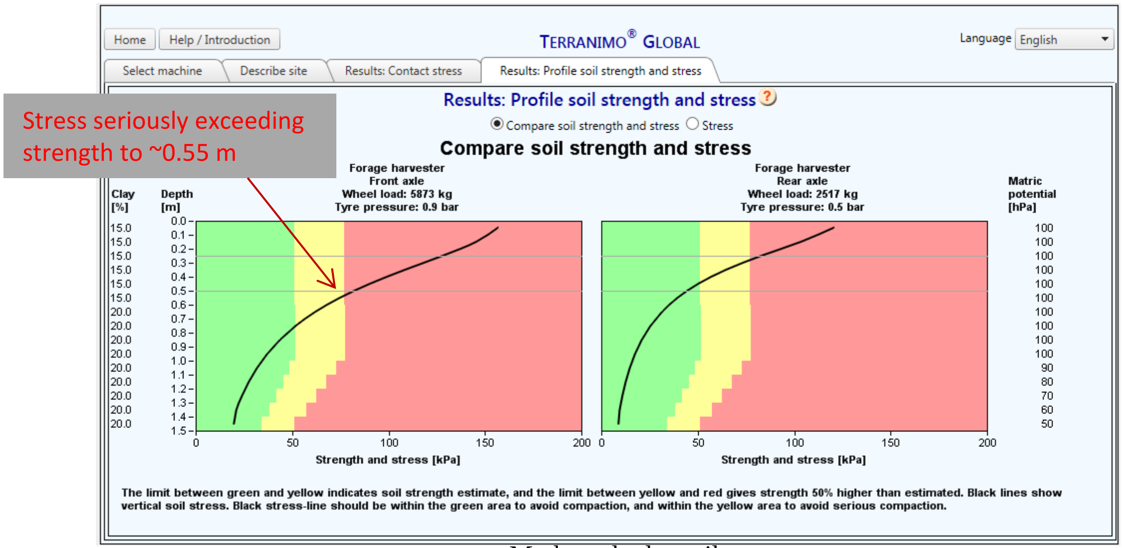



Figure 3. The contact area stress.
Here for a tractor-trailer combination with trailer tyres loaded with each ~60 kN (6 tonnes) and equipped with Nokian ELS 710/55R34 at 2.2 bar (first axle), Nokian ELS 710/55R34 at 1.2 bar (recommended)(middle axle) and Nokian ELS 800/50R34 at 1.0 bar (recommended)(rear axle).

## 10. Results: Profile soil strength and stress

The ‘Results: Profile soil strength and stress’ tab provides graphics comparing stress from the wheels with soil strength. Figure 4 illustrates the possibility of evaluating how stress and strength relate at two different moisture conditions for a forage harvester. The curved line depicts the stress from the wheel, while soil strength can be read as the boundary between the green and yellow areas of the plots. A stress level 150% that of the actual strength estimate is given as the boundary between the yellow and red area. Ideally, the stress line should be found within the green area for all soil depths,- at least for the non-tilled part of the soil profile. Serious compaction may be expected in case the stress line is within the red area. The case shown in Figure 4 indicates the importance of only driving on soils at moisture conditions that provide the necessary strength to carry the machines. Please consult the following sections to learn how stress and strength are calculated.

Field capacity moisture conditions




Moderately dry soil

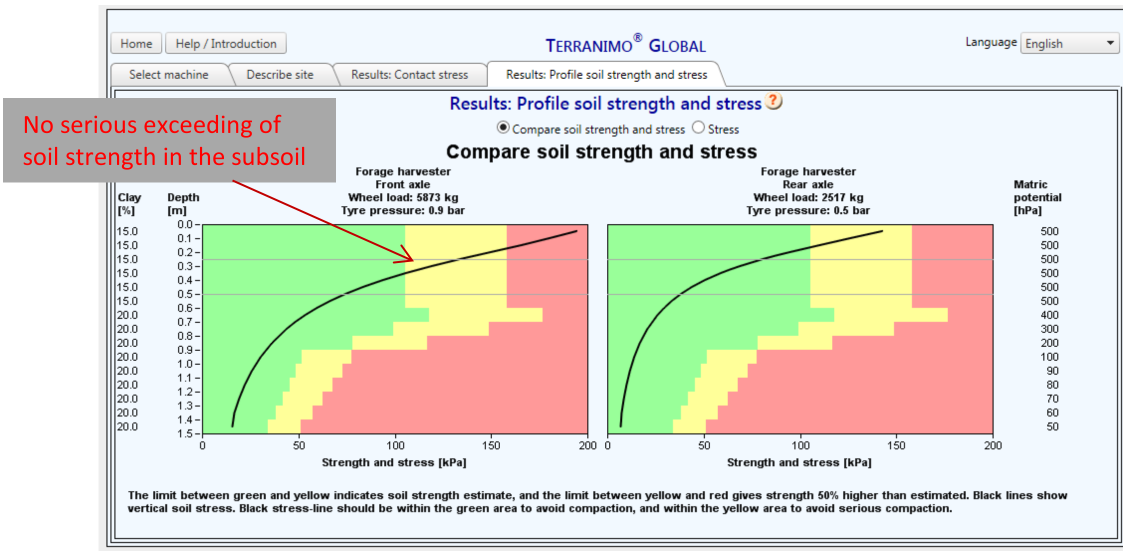



Figure 4. Comparison of stress and strength for the front and rear tyres of a forage harvester driving on a silty loam soil at field capacity moisture conditions (top) or when the soil is moderately dry (bottom).

### 11. Calculation of soil strength

Terranimo® estimation of soil strength is based on the principle behind the precompression stress concept. Soil is assumed to behave elastically with increase in stress up to the precompression stress level. At higher stresses, soil deformation is plastic / permanent (Horn, 1993). Although this concept has proven problematic (e.g., Cavallieri et al., 2008; Keller et al., 2011), it seems to be the best option for quantification of soil strength in a soil compaction context (Schjønning et al., 2015a). There is though a need for scaling the level of stress found from laboratory tests to the stress levels observed to induce plastic deformation in the field. Keller et al. (2012) found that soil from subsoil layers tested in natural field conditions at field capacity moisture content – independent on soil type – were able to withstand a vertical stress of approximately 40 kPa, while precompression stress values determined for the soils as determined in the lab were much higher. Higher precompression stress levels at that moisture condition have also been observed by other researchers (e.g., Fleige et al., 2002).

A data set on precompression stress was collected at Aarhus University (Schjønning and Lamandé, unpublished results). It includes a total of 584 field-sampled, undisturbed soil cores from nine locations (clay content range 4-17%) and four soil depths (0.3, 0.5, 0.8, 1.1 m), which were tested at three matric potentials (-50, -100 and -300 hPa; pF 1.7, 2.0, 2.5). The variation in precompression stress could be described by a combination of the matric water potential and soil content of clay (Figure 5). It appears that precompression stress is independent on soil type (soil content of clay) at a matric potential of -100 hPa (pF2). This is accordance with data of Cavallieri et al. (2008) and also with the field observations of soil strength by Keller et al. (2012).

The stress estimates in Figure 5 have been scaled to yield a constant value of approximately 50 kPa at pF2. This is to correspond to the field observed soil strength (Keller et al., 2012). We used 50 kPa rather than the previously mentioned 40 kPa because soil deformation in the field was negligible for small exceedings of the 40 kPa threshold (Keller et al., 2012).

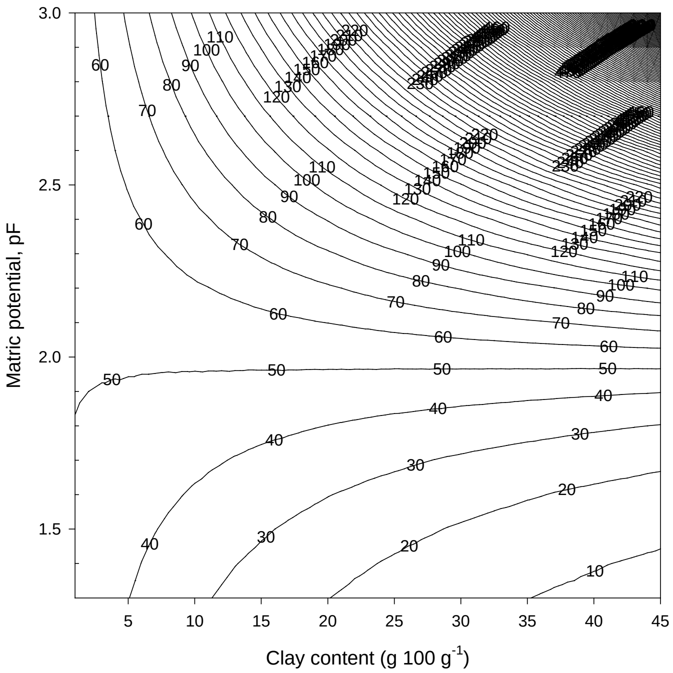



Figure 5. Estimates of soil strength (kPa) used in Terranimo® International as influenced by soil content of clay and the matric potential, expressed here as pF (small values: wet soil; high values: dry soil). Note that the strength estimates are regression-predicted based on measured precompression stress values scaled to yield 50 kPa at pF2.

The trend in soil strength reveals a decrease with increasing clay content for wet conditions (pF<2), while the opposite is the case for dry soil (Figure 5). This is in agreement with general experience, clay-holding soils being mechanically very weak when wet but strong when dry. Further, the increase in strength with decrease in matric potential (increase in pF) is much more prominent for clay-holding than for sandy soils. These trends were confirmed by analysis of another data set including a similar number of soils although only representing the 0.3-0.4 m soil layer (Schjønning, 1991)(not shown). The results of those tests have been implemented in the special Swiss version of Terranimo® (Stettler et al., 2014).

## 12. Calculation of stresses at the tyre-soil interface

Terranimo® takes use of the FRIDA model (Schjønning et al., 2008) to describe the vertical stresses exerted from the wheels to the soil surface. The FRIDA model describes the stress distribution in the directions along and across the driving direction by, respectively, a power-law function and a decay function (Keller, 2005). The contact area is described by a super-ellipse. Figure 5 shows measured and FRIDA-fitted stress distribution for a Michelin implement tyre.

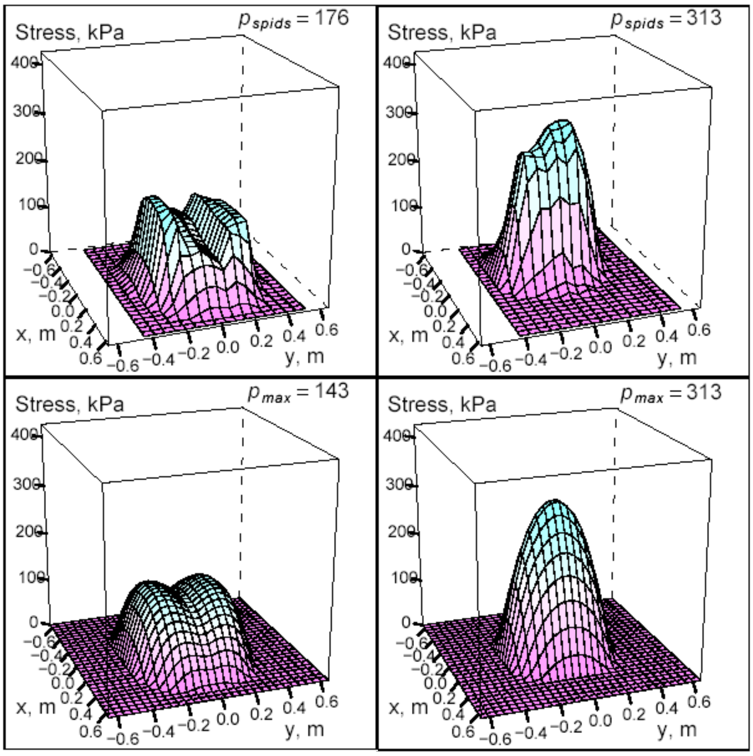



Figure 5. Measured vertical stress at the tyre-soil interface (upper part-Figures) and FRIDA-modelled stress-distribution (lower-part Figures). The data derives from a Michelin Cargoxbib 650/65R30.5 implement tyre loaded with ~60 kN (~6 tonnes) and either the recommended 1.0 bar (left) or 2.4 bar (right) inflation pressure. Data from Schjønning et al. (2006).

The Terranimo® tyre database includes more than 1000 different tyre types that can further be Terranimo-simulated for a countless number of wheel load – inflation pressure combinations. The stress distribution in the contact area for a user-selected combination is obtained from a collection of prediction equations relating the FRIDA model parameters to tyre dimensions, tyre inflation pressure and wheel load (Schjønning et al., 2015b).

The contact area of a tyre and hence the stress distribution is influenced by the strength of the topsoil. Terranimo® accounts for this as follows. First, the contact area is calculated from the loading characteristics of the selected tyre as mentioned above, using the pedotransfer functions provided by Schjønning et al. (2015b). Next, this estimate is modified based on the strength of the topsoil. We made a comparison between the large number of contact areas measured by Schjønning et al. (2006) for a not-recently-tilled field capacity soil and the estimates of tyre contact areas for either a 'soft' or a 'rigid' surface suggested by O'Sullivan et al. (1999). The calculated values from the O'Sullivan et al. (1999) equations appeared to fit reasonably to 1.4 or 0.7 times the Schjønning et al. (2006) measured values for 'soft' and 'rigid' surfaces, respectively (comparisons not shown). The 'soft' and 'rigid' conditions for not-recently-tilled soil were guesstimated to correspond to <=20 and >=300 kPa uncorrected precompression stress. The uncorrected precompression stress for soil at field capacity corresponding to a relative contact area equal of 1 was about 67 kPa. Based on these 'fix-points', we established a relation between the uncorrected precompression stress and the relative contact area (full line in Figure 6).

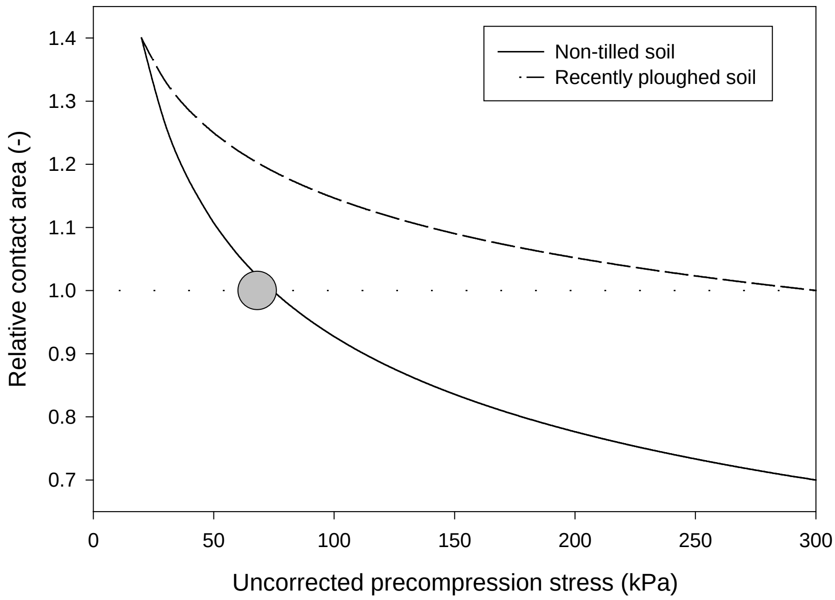



Figure 6. Terranimo® prediction of topsoil strength effects on the tyre-soil contact area. The gray symbol represents the topsoil strength condition for the comprehensive data set (Schjønning et al., 2006) being the main data behind the equations for estimating FRIDA parameters in Terranimo® (Schjønning et al., 2015b).

The topsoil strength influence on the contact area for a recently ploughed soil was estimated by field tests of stress distribution in the contact area for the Nokian ELS 800/50R34 that were carried out for a range of soil surface conditions (Schjønning et al., 2006; Lamandé and Schjønning, 2011ab; and unpublished data). This gave rise to the suggested relation between precompression stress and relative contact area displayed by the broken line in Figure 6. We note that this relation is less well supported by data than that for not-recently-tilled soil and should only be used for soil that has been ploughed recently.

The strength expressions in Figure 6 relate to different moisture conditions depending on soil content of clay. For example, for a soil with 10% clay the 20 kPa strength yielding a relative contact area of 1.4 corresponds to effective saturation (pF~0.2). The same topsoil strength (and relative contact area) would for a soil with 20% clay correspond to pF=1.1. The 300 kPa uncorrected precompression corresponds to about pF=4.2 for a soil with 10% clay, while that strength would be reached at pF=3.1 for a soil with 20% clay. In the specific Terranimo® code, the relative contact area is restricted to a maximum of 1.4. Similarly, constant relative contact areas of 0.7 and 1.0 for non-tilled and tilled soil, respectively, are used for topsoil strengths higher than 300 kPa.

### 13. Calculation of stresses in the soil profile

The vertical stresses in the soil profile below the wheels are calculated by the well-known Söhne (1953) approach with the FRIDA-estimated contact area point stresses as input. In accordance with Söhne, we modified the concentration of stresses according to soil strength. In Terranimo®, we assumed the originally suggested values of concentration factor ν=4 (‘hard’), ν=5 (‘firm’) and ν=6 (‘soft’) as corresponding to pF values of 2.7, 2.0 and 1.7, respectively. Taking further a pF value of 4.2 (the ‘wilting point’, i.e. a very dry soil) to correspond to total elasticity, we assumed ν=3 at those conditions. From non-linear regression, we obtained an exponential pedotransfer function to predict ν from the matric potential (pF). This means that the concentration factor used in Terranimo® varies continuously with the user-defined or DAISY-modelled matric potential of the soil. Figure 7 shows stress isobars below a Nokian ELS 710/55R34 mounted on a slurry trailer, loaded with ~60 kN (6 tonnes) and inflated to 2.2 bar. The tyre to the left illustrate stress transmission in a 20% clay soil at field capacity (pF=2.0, ν~5), while that to the right reflects the situation for a soil drained to the wilting point (pF=4.2, ν~3). Please note that in addition to the difference in concentration factor between the two simulations, also the contact area and the stress distribution in the contact area are affected by the change in moisture conditions. The net result is much higher topsoil stresses but lower subsoil stresses in the dry soil.

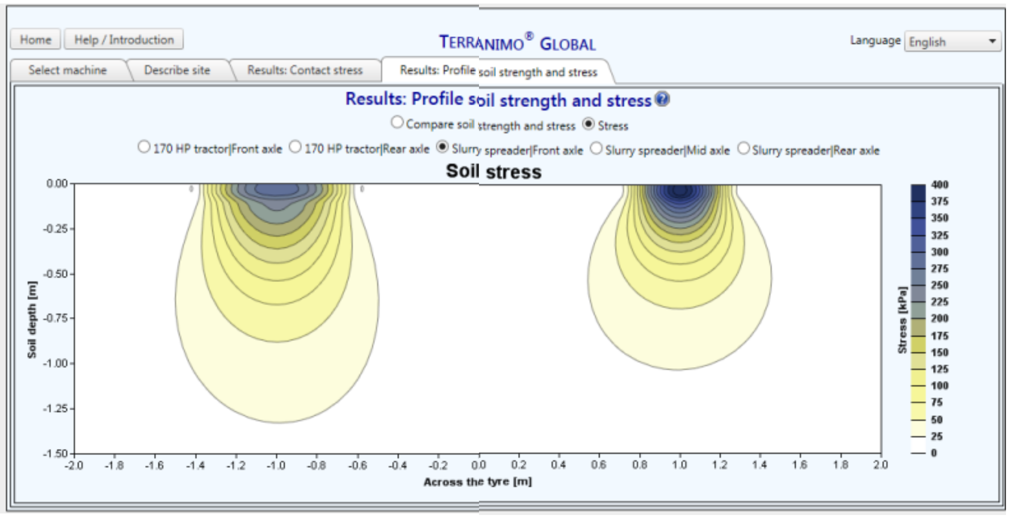



Figure 7. Terranimo-predicted stress distribution in the soil profile below a similarly loaded and inflated implement tyre at field capacity water content (left) and at the wilting point (right).

## 14. References


Abrahamsen, P., and Hansen, S. 2000. Daisy: An Open Soil-Crop-Atmosphere System Model. *Environ. Model. Software* 15, 313-330.

Cavalieri, K.M.V., Arvidsson, J., da Silva, A.P., Keller, T. 2008. Determination of precompression stress from uniaxial compression tests. Soil & Tillage Research 98, 17-26.

Fleige, R., Horn, R., Stange, F. 2002. Soil mechanical parameters derived from the CA-database Subsoil compaction. In: Pagliai, M. and Jones, R. (eds). Sustainable Land Management – Environmental Protection: a Soil Physical Approach. Advances in GeoEcology 35, Catena Verlag, Reiskirchen, Germany, pp. 359-366.

Horn, R. 1993. Mechanical properties of structured unsatured soils. Soil Technology 6, 47–75.

Keller, T. 2005. A model for the prediction of the contact area and the distribution of vertical stress below agricultural tyres from readily available tyre parameters. Biosystems Engineering 92, 85-96.

Keller, T., Arvidsson, J., Schjønning, P., Lamandé, M., Stettler, M., Weisskopf, P. 2012. In situ subsoil stress-strain behavior in relation to soil precompression stress. Soil Science 177, 490-497.

Keller, T., Lamandé, M., Schjønning, P., Dexter, A.R. 2011. Analysis of soil compression curves from uniaxial confined compression tests. Geoderma 163, 13-23.

Lamandé, M., Schjønning, P. 2011a. Transmission of vertical stress in a real soil profile. Part I: Site description, evaluation of the So¨hne model, and the effect of topsoil tillage. Soil & Tillage Research 114, 57–70.

Lamandé, M., Schjønning, P. 2011b. Transmission of vertical stress in a real soil profile. Part III: Effect of soil water content. Soil & Tillage Research 114, 78–85.

Lassen, P., Lamandé, M., Stettler, M., Keller, T., Jørgensen, M.S., Lilja, H., Alakukku, L., Pedersen, J., Schjønning, P. 2013. Terranimo® - A soil compaction model with internationally compatible input options. EFITA-WCCA-CIGR Conference "Sustainable Agriculture through ICT Innovation", Turin, Italy, 24-27 June 2013, 8pp.

O'Sullivan, M.F., Henshall, J.K., Dickson, J.W. 1999. A simplified method for estimating soil compaction. Soil & Tillage Research 49, 325-335.

Schjønning, P., Lamandé, M., Tøgersen, F.A., Arvidsson, J., Keller, T. 2008. Modelling effects of tyre inflation pressure on the stress distribution near the soil-tyre interface. Biosyst. Eng. 99, 119-133.

Schjønning, P., Lamandé, M., Tøgersen, F.A., Pedersen, J., Hansen, P.O.M. 2006. Minimering af jordpakning. Størrelse of fordeling af stress i trædefladen mellem hjul og jord (Reduction of soil compaction. Magnitude and distribution of stress in the contact area between wheel and soil). Report No. Markbrug 127, The Danish Institute of Agricultural Sciences, Tjele, Denmark. Available at: http://pure.au.dk/portal/files/458337/djfma127.pdf ; accessed 13/06/2014.

Schjønning, P., van den Akker, J.J.H., Keller, T., Greve, M.H., Lamandé, M., Simojoki, A., Stettler, M., Arvidsson, J., Breuning-Madsen, H. 2015a. Driver-Pressure-State-Impact-Response (DPSIR) analysis and risk assessment for soil compaction – a European perspective. Advances in Agronomy (in review).

Schjønning, P., Stettler, M., Keller, T., Lassen, P., Lamandé, M. 2015b. Predicted tyre-soil interface area and vertical stress distribution based on loading characteristics. Soil & Tillage Research (in review).

Söhne, W. 1953. Druckverteilung im Boden und Bodenformung unter Schleppereiffen (Pressure distribution in the soil and soil deformation under tractor tyres). Grundlagen der Landtechnik 5, 49-63.

Stettler, M., Keller, T., Weisskopf, P., Lamandé, M., Lassen, P., Schjønning, P. 2014. Terranimo® - a web-based tool for evaluating soil compaction. Landtech. 69, 2014, 132-137.


## 15. Contact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