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Unpublished note, Aarhus University, Dept. Agroecology

An introduction to Terranimo®

Note: Details in this text relates to the former version of Terranimo; will be updated asap

1. How to use this note

Sections 2-5 give some general information about the Terranimo® decision support tool. Sections 6-10 (+ 14) provide a short introduction to the use of the tool. And finally, sections 11-14 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 development of Terranimo®

Outcomes from projects funded by the Danish Ministry of Food, Fisheries and Agriculture included a relatively simple simulation model, "Jordværn online" (English: "SoilGuard online"), for soil stress distribution in the tyre-soil contact area (Schjønning et al., 2006). This tool took use of the mathematical model complex for describing the stress distribution along and across the driving direction suggested by Keller (2005). A modified version of the Keller model labelled 'FRIDA' – as later described by Schjønning et al. (2008) – was implemented in "Jordværn online". The model was parameterized by the FRIDA parameter prediction equations provided by Schjønning et al (2006).

Later, Thomas Keller from the ART Agricultural Research Station in Reckenholz and Matthias Stettler from the School of Agricultural, Forest and Food Sciences HAFL joined forces with Per Schjønning, Mathieu Lamandé, Poul Lassen and Margit S. Jørgensen from the Department of Agroecology at Aarhus University, Research Centre Foulum to create a decision support tool also including the mechanical strength of the soil. This model was called Terranimo® as described above.

Terranimo® is thus the work of an international team. In 2009-2012 the model development took place in a context of the ICT-AGRI funded project "PredICTor". In addition to the abovementioned group, the PredICTor project included Laura Alakukku from Helsinki University, Finland, and Harri Lilja from MTT Agrifood Research Finland. Also, Jan van den Akker, The Netherlands, Jan Rücknagel, Germany, and Henrik Breuning-Madsen and Jørgen Pedersen from Denmark were associated to the PredICTor project.

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, Dutch, Dutch (Flemish), Norwegian, Swedish, Finnish or Danish. For the time being, five national versions are available: Denmark, Norway, Finland, Switzerland and Belgium-Flanders. 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 to assess, whether stresses exceeds the soil mechanical strength – hence likely inducing plastic/permanent deformation of the soil – for a specific traffic event.

6. General aspects of the user interface

When starting Terranimo®, the user is met with a screen showing pre-selected machinery, which is a tractor-trailer combination for slurry application (Figure 1). It is possible to do simulations without logging in as a user. However, in case data entered should be re-used after closing down Terranimo®, the user should login by clicking the 'Login' tab (Figure 1). By contacting Poul Lassen (Poul.Lassen@agro.au.dk), you will be provided a password (no info on user identity will be asked for, and the use of Terranimo® is still free of charge).

Terranimo® includes 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). 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 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.

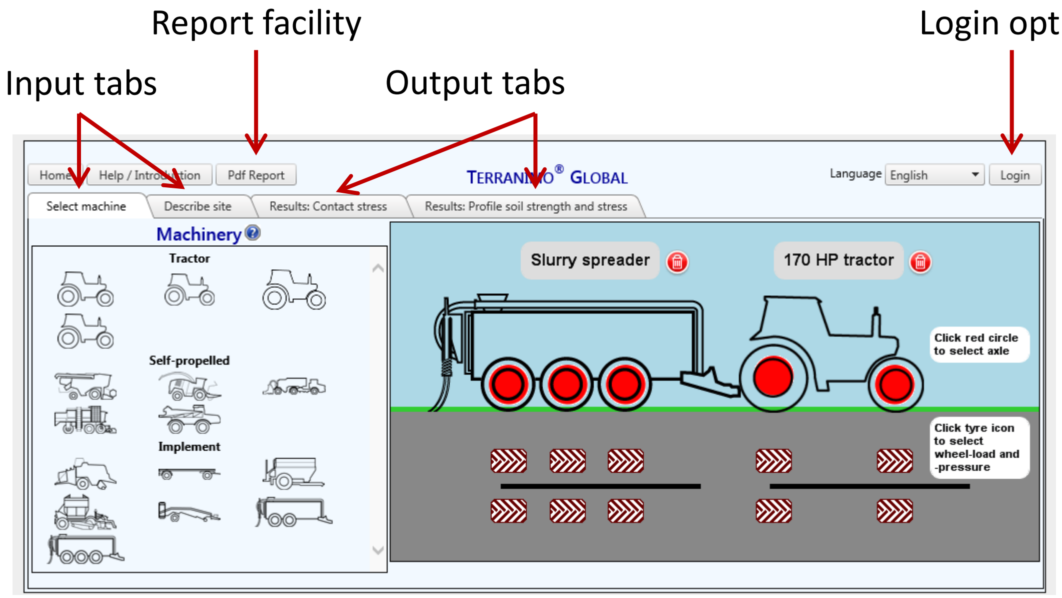


Figure 1. The opening window when starting up Terranimo®. The report facility is described in section 14.

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.

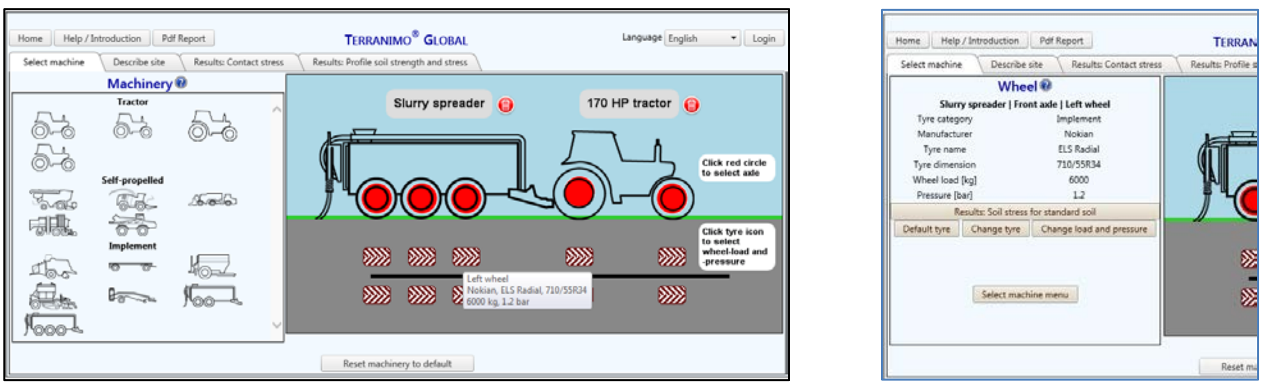


Figure 2. Tyre type, wheel load and tyre inflation pressure is shown for wheels on the machinery if placing the cursor on top of the tyre icons (left). If clicking the icons, a menu opens, enabling change of tyre and modifications in wheel load and inflation pressure for the selected tyre (right).

Pop-up boxes with info on tyre type, wheel load and inflation pressure appears when holding the cursor above the tyre icons (Figure 2, left). By clicking the tyre icon, a sub-menu allows for changing tyres, and for modifying wheel loads and inflation pressures (Figure 2, right).

Clicking the 'Results: Soil stress for standard soil' button on the menu in Figure 2 (right) opens up graphics showing the periphery of the tyre soil contact area, the stress distribution in the contact area, and the stress distribution in the soil profile if the specific tyre in question would traffic a sandy soil at a water content of field capacity (in a Terranimo® context, the 'standard' soil)(Figure 3). Thus, please note that this facility is unaffected by the selection of soil texture and water conditions in the 'Describe site' tab (as explained below).

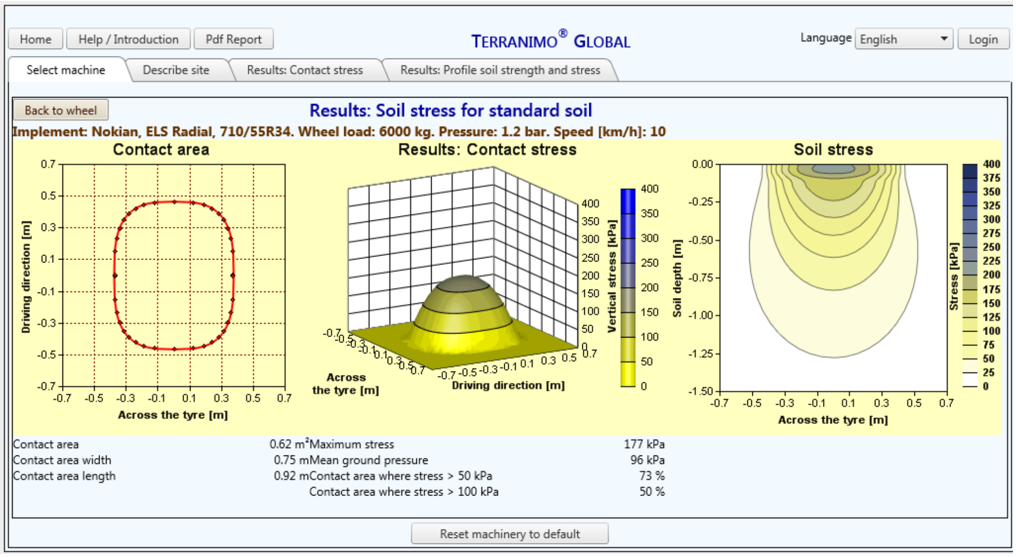


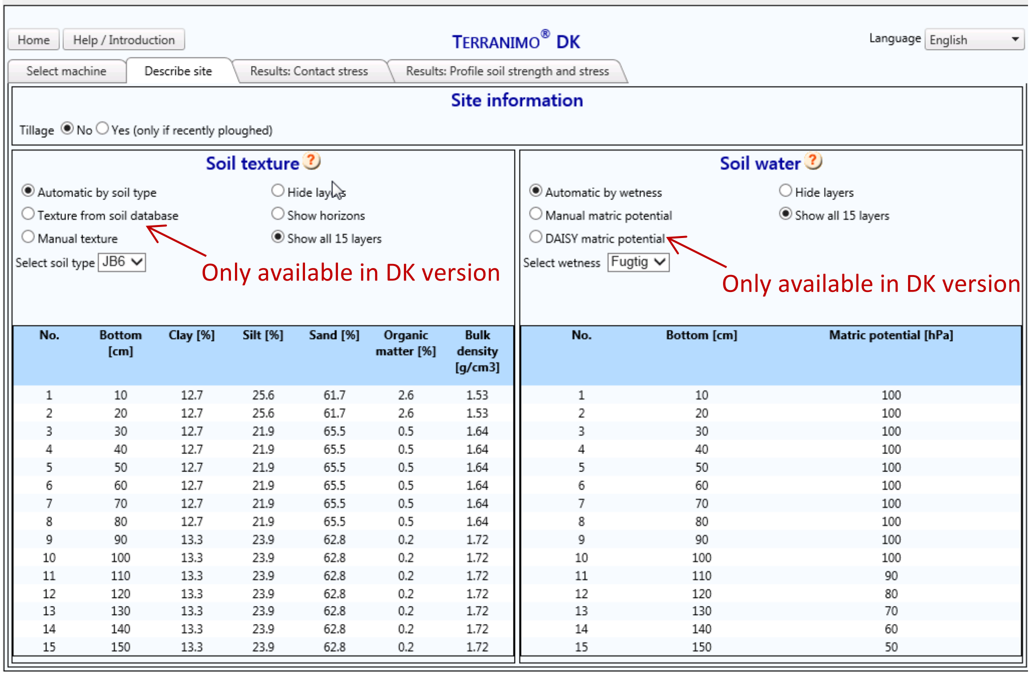
Figure 3. A special facility allows for studying the performance of a selected tyre at the selected wheel load and inflation pressure. Importantly, this specific graphics relate to 'standard' soil conditions, which in Terranimo® is defined as a sandy soil at field capacity water conditions.

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 4). 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 4).

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.

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 4. ‘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 4). As for soil texture, users may manually input matric potentials in case these are known,- f.ex. from tensiometer readings (‘Manual matric potential’, Figure 4).



No.	Bottom [cm]	Clay [%]	Silt [%]	Sand [%]	Organic matter [%]	Bulk density [g/cm3]
1	10	12.7	25.6	61.7	2.6	1.53
2	20	12.7	25.6	61.7	2.6	1.53
3	30	12.7	21.9	65.5	0.5	1.64
4	40	12.7	21.9	65.5	0.5	1.64
5	50	12.7	21.9	65.5	0.5	1.64
6	60	12.7	21.9	65.5	0.5	1.64
7	70	12.7	21.9	65.5	0.5	1.64
8	80	12.7	21.9	65.5	0.5	1.64
9	90	13.3	23.9	62.8	0.2	1.72
10	100	13.3	23.9	62.8	0.2	1.72
11	110	13.3	23.9	62.8	0.2	1.72
12	120	13.3	23.9	62.8	0.2	1.72
13	130	13.3	23.9	62.8	0.2	1.72
14	140	13.3	23.9	62.8	0.2	1.72
15	150	13.3	23.9	62.8	0.2	1.72

No.	Bottom [cm]	Matric potential [hPa]
1	10	100
2	20	100
3	30	100
4	40	100
5	50	100
6	60	100
7	70	100
8	80	100
9	90	100
10	100	100
11	110	90
12	120	80
13	130	70
14	140	60
15	150	50

Figure 4. The user interface for input of soil texture and moisture conditions (tab ‘Describe site’).

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 5 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 5).

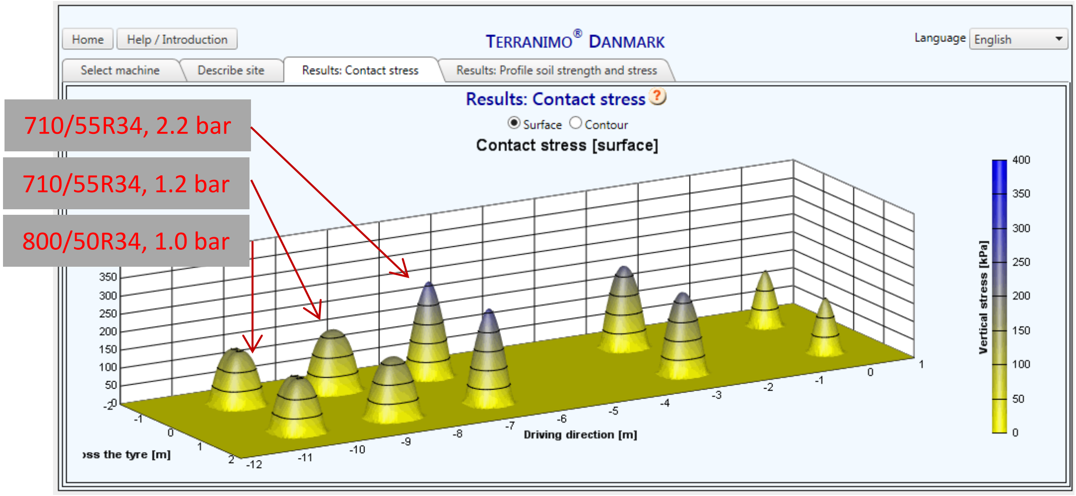
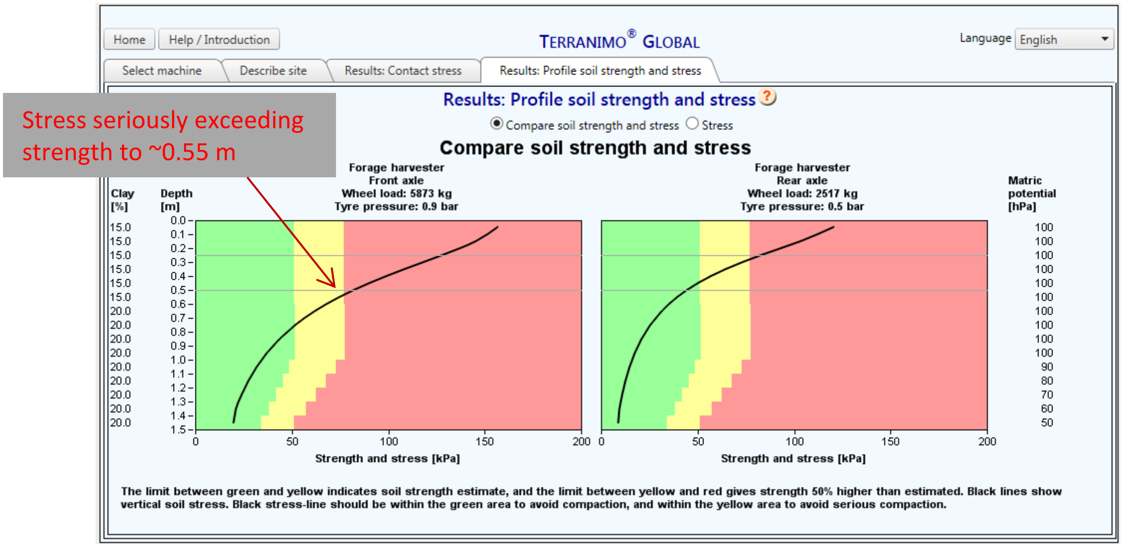


Figure 5. The contact area stress.
Here for a tractor-trailer combination with trailer tyres loaded with each ~60 kN (6 tonnes) and equipped with Nokian ELS 710/55R34 at 2.2 bar (first axle), Nokian ELS 710/55R34 at 1.2 bar (recommended)(middle axle) and Nokian ELS 800/50R34 at 1.0 bar (recommended)(rear 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 6 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 6 indicates the importance of only driving on soils at moisture conditions that provide the necessary strength to carry the machines.

Field capacity moisture conditions



Moderately dry soil

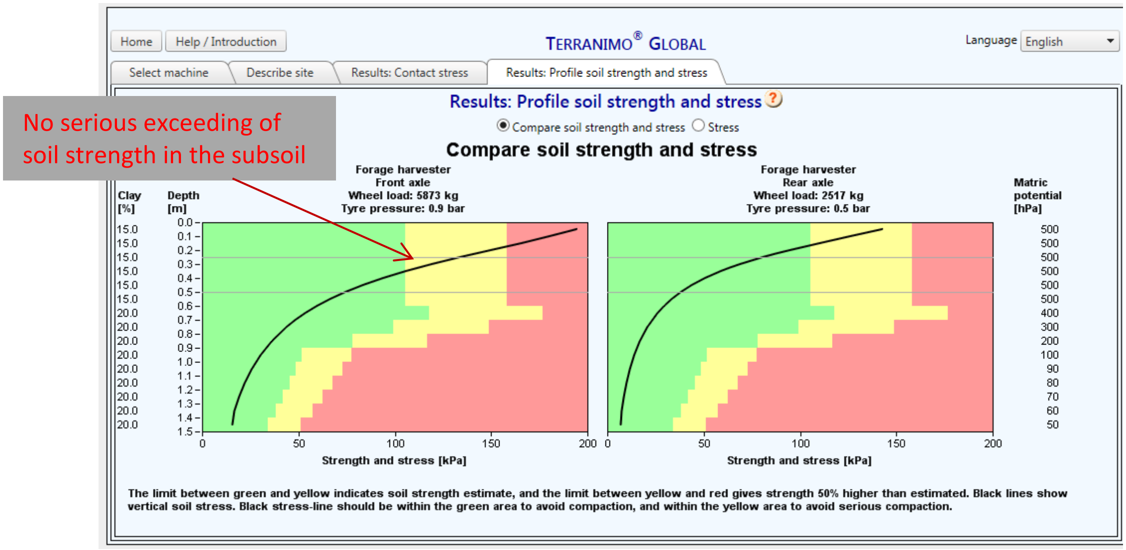


Figure 6. Comparison of stress and strength for the front and rear tyres of a forage harvester driving on a silty loam soil at field capacity moisture conditions (top) or when the soil is moderately dry (bottom).

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; Figure 7). 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).

In Figure 7, the precompression stress (soil strength) is given by the breakpoint of the stress-strain plot with stress given in a logarithmic scale. The colours of the log(stress) – strain lines correspond to the colours in Figure 6: Green for stresses smaller than soil strength, yellow for stresses exceeding soil strength to 150% the soil strength, and red for stresses exceeding 150% the strength.

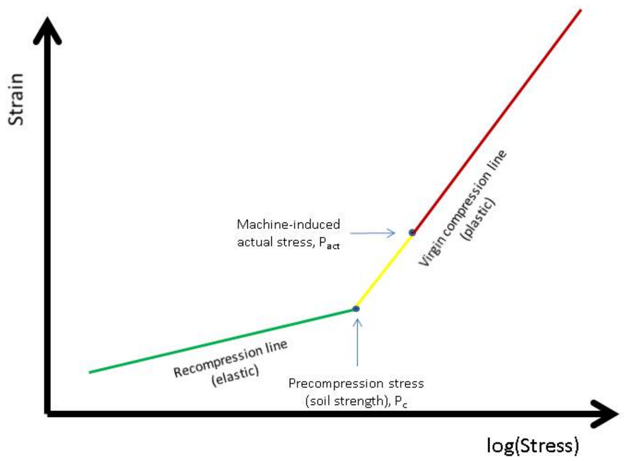


Figure 7. Sketch of the principles in determination of the precompression stress (soil strength) from laboratory tests, and the use of the stress-strength relation in Terranimo®. In real laboratory tests of soil, the transition between the elastic and plastic stress ranges is not as distinct as in the Figure. This is the reason for giving a red alert only when stress exceeds soil strength by 50%. The colours of the log(stress) – strain lines (green, yellow, red) correspond to those used in Figure 6 for advising on the risk of permanent compaction. Thus, for the conditions shown, $P_{act} = 1.5 \times P_c$.

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, the soil bulk density, and the soil content of clay. It appeared 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 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 (not shown). 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. Finally, precompression stress increases with increase in soil bulk density. 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 8 shows measured and FRIDA-fitted stress distribution for a Michelin implement tyre.

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).

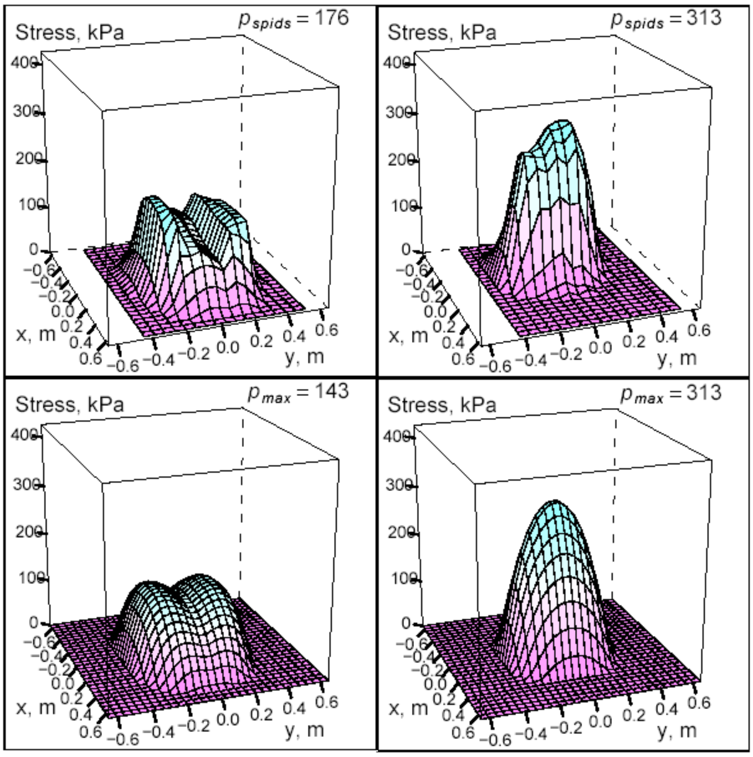


Figure 8. Measured vertical stress at the tyre-soil interface (upper part-Figures) and FRIDA-modelled stress-distribution (lower-part Figures). The data derives from a Michelin Cargoxbib 650/65R30.5 implement tyre loaded with ~60 kN (~6 tonnes) and either the recommended 1.0 bar (left) or 2.4 bar (right) inflation pressure. Data from Schjønning et al. (2006).

The 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 precompression stress. The precompression stress for soil at field capacity and with a typical bulk density corresponding to a relative contact area equal of 1 was about 67 kPa. Based on these 'fix-points', we established a relation between the precompression stress and the relative contact area (full line in Figure 9).

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 9. 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.

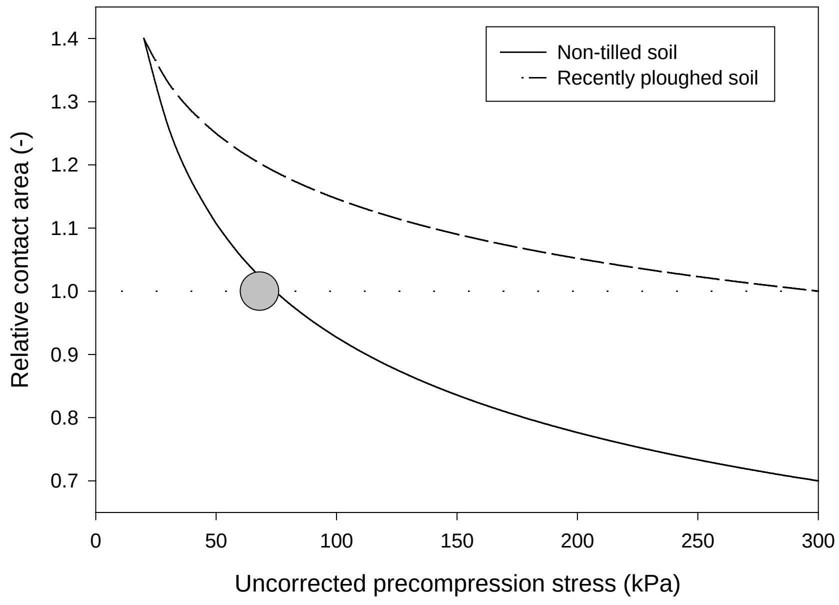


Figure 9. Terranimo® prediction of topsoil strength effects on the tyre-soil contact area. The gray symbol represents the topsoil strength condition for the comprehensive data set (Schjønning et al., 2006) being the main data behind the equations for estimating FRIDA parameters in Terranimo® (Schjønning et al., 2015b).

The strength expressions in Figure 9 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 10 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 the same 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 (the depth of stress penetration), 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 than the moist soil.

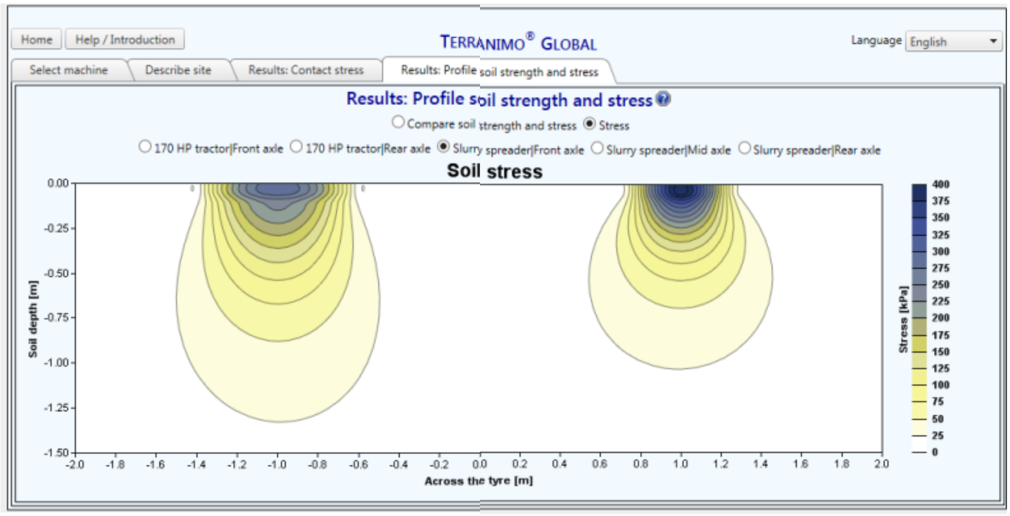


Figure 10. Terranimo-predicted stress distribution in the soil profile below a similarly loaded and inflated implement tyre at field capacity water content (left) and at the wilting point (right).

14. Report facility

A report facility allows for saving the simulation results for further inspection and analyses. Following selection of machinery (including tyre types, wheel loads, and tyre inflation pressures), soil texture, and soil water conditions, the results may be inspected online in the two output windows as explained in sections 9 and 10. If at this point activating the 'Pdf Report' tab (Figure 1), the system will generate a report including the visual presentations found online, but in addition Tables with calculated values of contact area, mean ground pressure, maximum stress in the contact area, and stress and strength for soil depths in 10 cm increments to 150 cm. The report can be accessed by clicking a 'Report' icon that will be displayed next to the 'Pdf Report' tab when the report has been generated. Please consult the final four pages of this note for a sample report. The user may save reports on his/her computer for later inspection.

Importantly, the output tabs 'Results: Contact stress' and 'Results: Profile soil strength and stress' need to be activated before creating the report in order to obtain correct graphics in the report.

In the report, the risk of soil compaction is indicated by calculation of a soil compaction index (SCI) in addition to the visual comparison of stress and strength. This index was suggested by Rücknagel et al. (2015):

$$SCI = \log(P_{act}/P_c) \qquad (1)$$

where P_{act} is the calculated, actual vertical stress, and P_c is soil strength (the scaled precompression stress, see section 12). The green, yellow and red levels of soil compaction risk displayed in Figure 6 (and Figure 7) correspond to $P_{act}/P_c<1$, $1<P_{act}/P_c<1.5$ (stress exceeding strength by 50%), and $P_{act}/P_c>1.5$, respectively. This, in turn, corresponds to SCI<0, 0<SCI<0.18, and SCI>0.18. Negative values of SCI (stress lower than strength; no risk of compaction) are given as zeroes in the report. Hence, the risk of soil compaction may be evaluated quantitatively. SCI should ideally be zero for all soil depths, and values higher than ~0.2 is a serious alert. For the tilled topsoil layer (typically 0-20 cm), SCI nearly always will be higher than zero, but subsequent tillage as well as wet-dry and frost-thaw events may ameliorate the damage for that layer.

The values of SCI may be used for providing an estimate of plastic soil deformation (degree of permanent compaction). Soil deformation is expected to be linearly correlated with SCI (Figure 7). As an example, the strain induced by SCI values of 0.4 would most probably be double that experienced when SCI is 0.2.

The impact of a given deformation on soil functions, in turn, is very complicated and cannot be easily modelled. Therefore, sustainability may be judged from SCI alone, and values exceeding 0.2 especially in deep subsoil should be avoided.

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16. Contact

The Terranimo® soil compaction group may be contacted by emailing Per Schjønning at: Per.Schjonning@agro.au.dk

Questions regarding system development and potential malfunctions of the web tool may be directed to Poul Lassen at: Poul.Lassen@agro.au.dk

Report from simulation with Terranimo

Date: 15 April 2016

Terranimo version: Danmark

Selected machinery

170 HP tractor with Slurry spreader

Table 1. Loading characteristics for all wheels of the machine system.

Axle	Manufacturer	Tyre category	Tyre dimension	Wheel load [kg]	Pressure [bar]	Recommended pressure [bar]
Front axle	Michelin	Traction	480/70R24	868	0.4	0.4
Rear axle	Michelin	Traction	580/70R38	5402	1.8	1.8
Front axle	Nokian	Implement	710/55R34	6000	1.2	1.2
Mid axle	Nokian	Implement	710/55R34	6000	1.2	1.2
Rear axle	Nokian	Implement	710/55R34	6000	1.2	1.2

See a sketch of the machinery in Appendix 1.

Soil and soil water

You have simulated for a soil with 12.7 % clay content (topsoil, average 0-20 cm) and 100 hPa matric potential in the topsoil. Detailed data for soil texture and soil matric potential are found as tables in Appendix 2.

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The tyre-soil contact area

Table 2. Key figures for the stress distribution in the tyre-soil contact area.

Axle	Contact area [m^2]	Mean ground pressure [kPa]	Maximum stress [kPa]
Front axle	0.306	28	55
Rear axle	0.481	110	204
Front axle	0.632	93	170
Mid axle	0.632	93	170
Rear axle	0.632	93	170

A graph showing the contact area stress distribution for all tyres is displayed in Appendix 3.

Report from simulation with Terranimo

Soil profile stress

The vertical stress right below the center of each tyre is tabulated below. For most tyres and inflation pressures, these data will indicate the highest stresses affecting the soil profile,- at least for soil depths deeper than ~0.3 m.

Table 3. Vertical soil stress (kPa) in a line under the center of the tyre for all tyres on the machinery.

Axle	**Soil depth [m]**														
	0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
Front axle	51	42	32	24	19	14	11	9	7	6	5	4	4	3	3
Rear axle	198	177	148	120	96	77	63	51	43	36	31	26	23	20	19
Front axle	166	153	134	113	93	77	64	53	45	38	33	28	25	22	20
Mid axle	166	153	134	113	93	77	64	53	45	38	33	28	25	22	20
Rear axle	166	153	134	113	93	77	64	53	45	38	33	28	25	22	20

Soil profile strength and stress

Soil compaction will take place if stress exceeds soil strength. A comparison can be made between the two. Severe compaction will occur in case stress exceeds the soil strength significantly.

Table 4. Soil compaction index (SCI) calculated as the log to the ratio of stress and strength (see section 14 in the Terranimo Introduction file).

Axle	**Soil depth [m]**														
	0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
Front axle	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rear axle	0.47	0.42	0.29	0.20	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Front axle	0.39	0.36	0.25	0.17	0.09	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mid axle	0.39	0.36	0.25	0.17	0.09	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rear axle	0.39	0.36	0.25	0.17	0.09	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

SCI=0: No compaction risk. 0<SCI<0.2: Intermediate compaction risk. SCI>0.2: High compaction risk.

A graph showing the soil profile stress and strength for all tyres is displayed in Appendix 4.

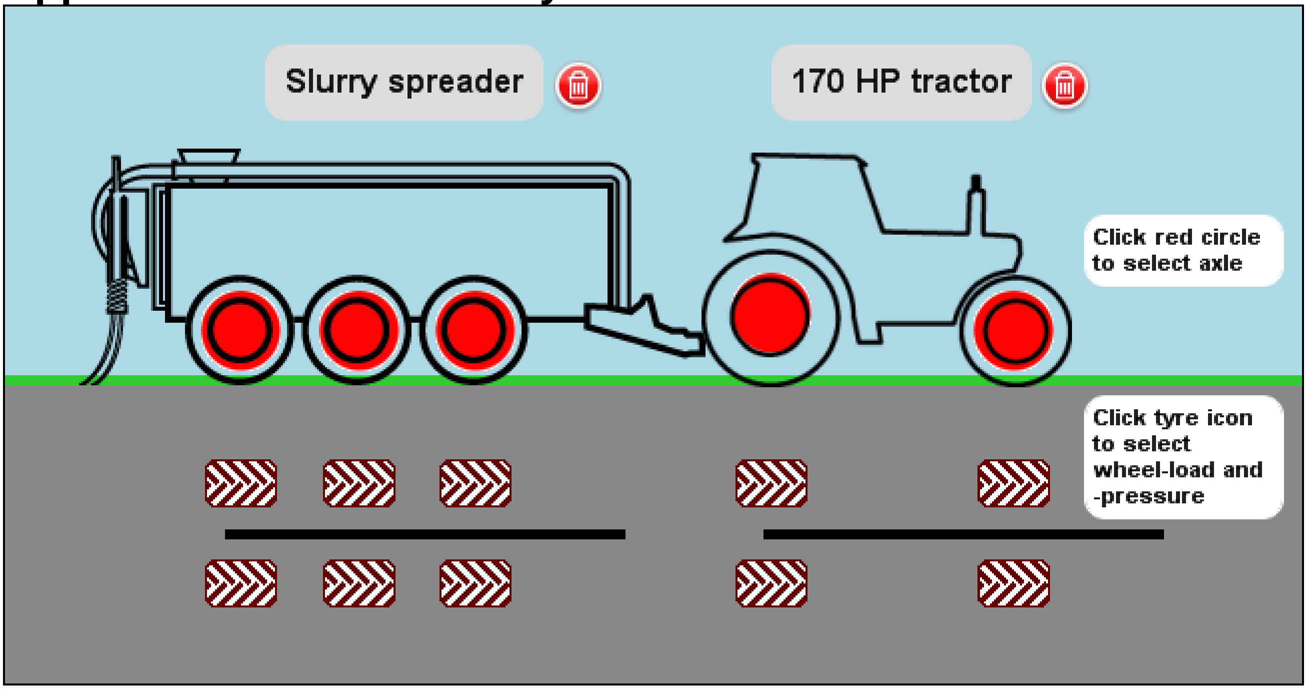
Recommendation

If SCI>0.2 (especially if this is the case for layers deeper than 0.5 m), the intended traffic should not be undertaken. We suggest one or more of the following actions: Change tyre, reduce inflation pressure (primarily affecting stresses in upper soil layers), reduce wheel load (primarily affecting stresses in the deeper soil layers), wait with the intended traffic to soil water content has reduced (which will increase soil strength).

Comments

Report from simulation with Terranimo

Appendix 1: Soil machinery used for simulation

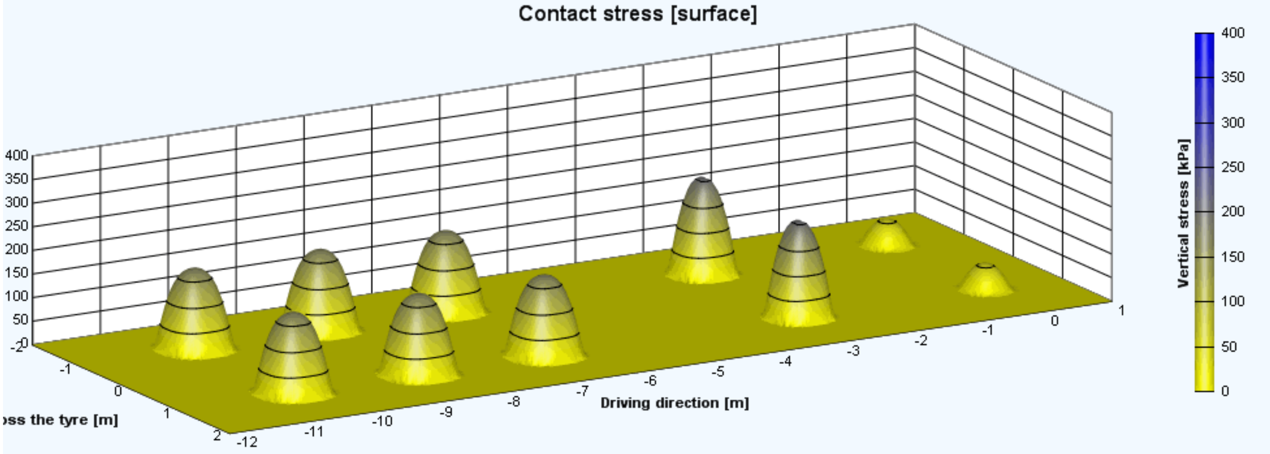


Appendix 2: Detailed data on texture and water

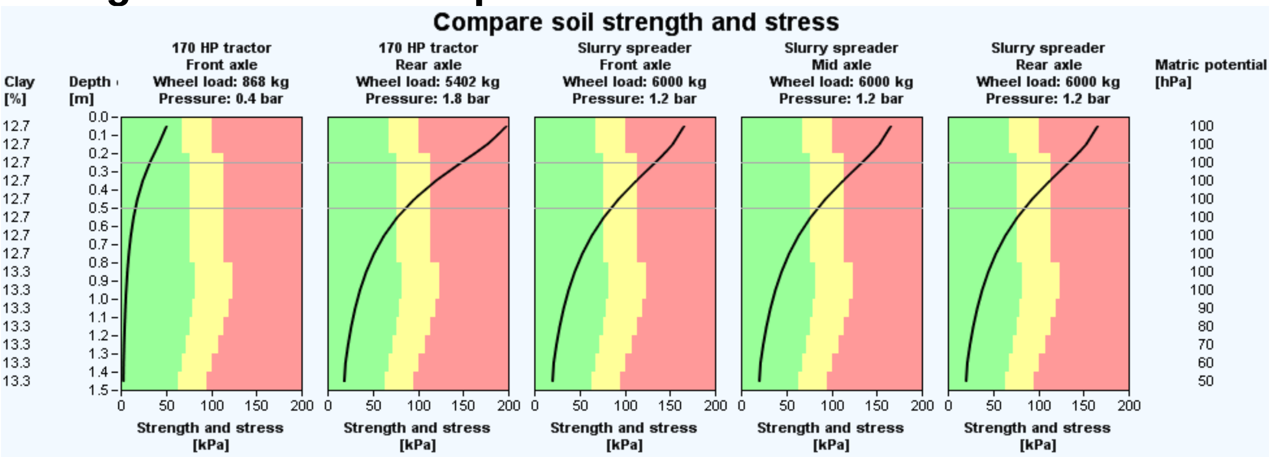
Soil depth [m]	Clay [%]	Silt [%]	Sand [%]	Organic matter [%]	Bulk density [g/cm3]	Matric potential [hPa]	Soil strength [kPa]
0.1	12.7	25.6	61.7	2.6	1.5	100	67
0.2	12.7	25.6	61.7	2.6	1.5	100	67
0.3	12.7	21.9	65.5	0.5	1.6	100	76
0.4	12.7	21.9	65.5	0.5	1.6	100	76
0.5	12.7	21.9	65.5	0.5	1.6	100	76
0.6	12.7	21.9	65.5	0.5	1.6	100	76
0.7	12.7	21.9	65.5	0.5	1.6	100	76
0.8	12.7	21.9	65.5	0.5	1.6	100	76
0.9	13.3	23.9	62.8	0.2	1.7	100	83
1.0	13.3	23.9	62.8	0.2	1.7	100	83
1.1	13.3	23.9	62.8	0.2	1.7	90	79
1.2	13.3	23.9	62.8	0.2	1.7	80	76
1.3	13.3	23.9	62.8	0.2	1.7	70	72
1.4	13.3	23.9	62.8	0.2	1.7	60	68
1.5	13.3	23.9	62.8	0.2	1.7	50	63

Report from simulation with Terranimo

Appendix 3: Graph with stresses in the tyre-soil contact area



Appendix 4: Graph comparing stresses from the wheels with soil strength for all the soil profile



The limit between green and yellow indicates soil strength estimate, and the limit between yellow and red gives strength 50% higher than estimated. Black lines show vertical soil stress.

The intended traffic should not be undertaken if the black line runs within the red area (especially for layers deeper than 0.5 m). We suggest one or more of the following actions: 1) change tyre, reduce inflation pressure (primarily affecting stresses in upper soil layers), 2) reduce wheel load (primarily affecting stresses in the deeper soil layers), and/or 3) wait with the intended traffic to soil water content has reduced (which will increase soil strength).