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Terranimo® – a web-based tool for evaluating soil compaction

Based on experimental data from wheeling experiments, a web-based model for the simulation of stress and the evaluation of the soil compaction risk under agricultural machinery named Terranimo® has been developed. Terranimo® incorporates a model for prediction of contact area, shape and stress distribution in the tyre–soil interface from wheel load and readily-available tyre parameters and the topsoil strength. In Terranimo® pedotransfer functions are used to estimate soil strength from clay content and matric potential. Principally, by limiting the imposed stress to below soil strength, the risk of soil compaction and undesirable changes of soil structure – and hence soil functions – can be minimized.

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Tyres, stress distribution, stress propagation, soil strength, soil compaction risk

Abstract

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Soil compaction by heavy agricultural machinery has long-lasting impacts on the pore system in the soil, particularly in the subsoil, and adversely affects important soil functions such as fertility and water infiltration capacity. Long-term studies have shown that subsoil compaction is not appreciably remedied by natural processes and that nutrient leaching and greenhouse gas emissions may be intensified in the long run [1].

Terranimo® is a web-based computer model for evaluating the risk of soil compaction under agricultural vehicles and is primarily designed for farmers, agricultural contractors, consultants, and enforcement authorities, but has scientific applications as well. Terranimo® can help in optimizing the use of agricultural machinery in the field and in preventing damage to the soil structure by indicating the use conditions under which there is a high risk of harmful soil compaction occurring.

Since the summer of 2013, Terranimo® has been the official tool in Switzerland for evaluating the soil compaction risk in the scope of the "Soil Protection in Agriculture" (Bodenschutz in der Landwirtschaft) implementation guidance of the Federal Office for Agriculture (FOAG) and of the Federal Office for the Environment (FOEN) [2]. The model is therefore also of relevance to environmental law. Terranimo® is available free of charge at www.soilcompaction.ch.

The basic principle of Terranimo®

The basic idea behind Terranimo® is simple and not new: The stress (pressure) exerted on the soil by agricultural equipment is balanced with the capacity of the soil to resist compaction (soil strength). If the soil strength is greater than the soil stress, then no permanent deformation will occur and hence soil damage is not to be expected. If this is not the case, then soil compaction is unavoidable and one should refrain from driving on the soil.

Correct assessment of soil stress and soil strength is required for correct predictions. Greater demands for precision in simulation require greater effort for the exact description of the field situation. Thus in order to satisfy a wide variety of user demands, two versions of the model were developed: Terranimo® light for a simple and quick rough assessment and Terranimo® expert for a detailed analysis of the soil compaction risk under specific conditions.

Terranimo® light: risk assessment made easy

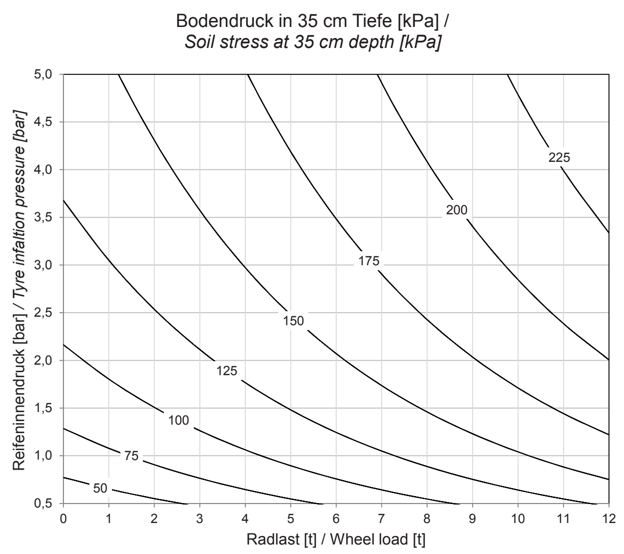
Terranimo® light enables a quick assessment of the soil compaction risk by using four parameters: wheel load, tyre inflation pressure, soil moisture and clay content.

Wheel load and tyre inflation pressure are the input variables on the machine side for calculating soil stress. A soil depth of 35 cm serves as a reference. This value is based on the existing prescriptions on soil protection in the Swiss construction sector [3]. The justification for it resides in the fact that soil damage at this depth can only be remedied with considerable effort and years of careful subsequent management.

The formula for calculating soil stress is based on extensive wheeling experiments conducted at Aarhus University in Denmark using different tyres and under different combinations of wheel loads and tyre inflation pressures [4; 5]. The analyses showed that wheel load and tyre pressure can describe soil stress with sufficient precision for a given soil depth regardless of the brand and type of tyre. This relationship is illustrated for the reference depth of 35 cm in **Figure 1** in the form of a nomogramm. The contour lines clearly show that wheel load and tyre inflation pressure are similarly decisive for soil stress at 35 cm soil depth. In other analyses not shown here, it was demonstrated that the influence of tyre inflation pressure predominates in shallow soil layers, whereas wheel load becomes the determining factor in deeper layers [5; 6]. The familiar rule of thumb was thus confirmed: Tyre inflation pressure determines the stress in the topsoil, whereas wheel load determines the stress in the subsoil.

Oedometer readings taken in the Aarhus University laboratory on some 500 soil samples with clay contents of 5–18 % and with different matric potentials (3, 5, 7.5, 10, 16, and 30 cbar) served as the basis for determining the input variables on the soil side for soil strength [7]. Matric potential (water suction) is a measurement of the water availability in the soil; it essentially describes the attraction forces between soil moisture and soil particles. For a specific soil with a given pore size distribution, there is a direct correlation between matric potential and moisture content. The compression index of undisturbed soil samples in cylindrical probes can be determined by performing compression tests in the oedometer. In the present case, the Gompertz equation was used to calculate the precompression stress from the compression curves, as in Gregory et al. [8]. Precompression stress describes the pressure point at which the behaviour of a soil sample transitions from elastic to plastic. As long as the compression stress stays below the precompression stress, a soil sample will spring back to its original shape once the stress is relieved and no permanent deformation occurs. The soil sample does not become compacted. If the precompression stress is exceeded, however, irreversible plastic deformations occur: Even when the stress is relieved, there is still permanent settling and the soil sample is compacted.

Fig. 1



Soil stress nomogramm (adapted from [5]): The contour lines show the stress at 35 cm soil depth as a function of wheel load and tyre inflation pressure

Terranimo® uses precompression stress as a measurement for soil strength, which is in keeping with a widely-used approach [9]. On the basis of the Aarhus University data set, it was possible to describe soil strength as a function of matric potential and clay content [10]. The corresponding pedotransfer function thus allows a universal estimation.

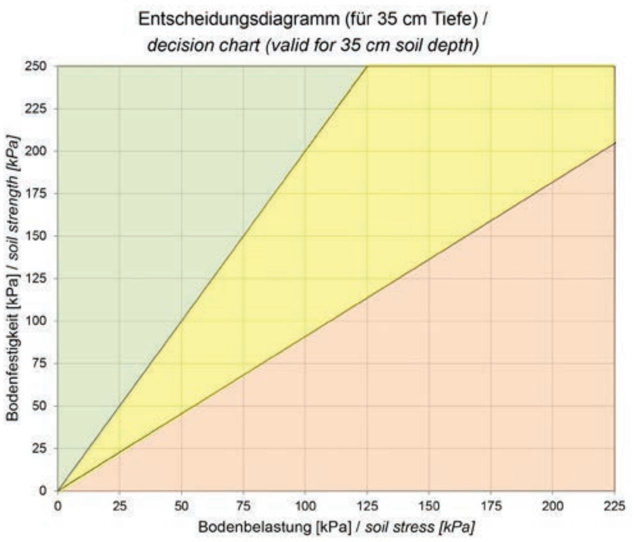
An analysis of the absolute precompression stress values of Arvidsson and Keller [11], of Rücknagel et al. [12] and of the values calculated in Terranimo showed that the results are comparable, even for very heavy soils (up to 60 % clay), even though there was considerable variation in the measurement values of [11] and [12]. However, it is not easy to compare different data sets because the precompression stress value is dependent upon the test conditions (especially upon the duration of stress) and the sample dimensions [13].

As concerns soil strength, however, the relationships are somewhat more complex than for soil stress. The parameters interact with one another: Matric potential has variable impacts on soil strength, depending upon clay content. Light soils with low clay content are in principle more stable than heavy soils under moist conditions (matric potential < 10 cbar), but as they dry out they experience significantly lesser increases in soil strength than is the case with clay-rich soils. The effect of clay content is relatively minor around field capacity (matric potential ca. 10 cbar). This finding is consistent with those of studies by Cavaglieri et al. [14], in which nearly identical precompression stress values were found for different soil types with moisture contents around field capacity.

In Terranimo® light, the values calculated for soil stress and soil strength are presented in the form of a three-coloured decision chart (**Figure 2**). The risk of compaction under the current conditions is assigned to one of three hazard levels (green, yellow, or red) [2]:

- Green: no risk of compaction. The chosen vehicle can be driven on the soil in its present moisture state with no hazard of compaction.
- Yellow: critical transition zone with a considerable risk of compaction. In this case knowledge of additional soil properties will allow a more precise risk assessment. For example, the hazard will decrease in stony (> 10 % stones in the subsoil) and in well-structured soils (owing to, e.g., conservation tillage, extensive root penetration, high humus content or good lime supply). In each case all possible means of stress reduction (e.g., lowering tyre pressure, only filling hoppers partially, or mounting twin tyres) should be implemented.
- Red: compaction damage to the subsoil is to be expected. One must refrain from driving on the soil unless suitable immediate measures can be taken to reduce the compaction hazard to the yellow level (e.g., reducing the wheel load or tyre pressure).

Fig. 2



The decision chart as presented in Terranimo®, relating soil stress to soil strength and classifying the compaction risk into three levels (green, yellow, red)

The border between the green and yellow hazard levels corresponds to a soil stress equal to 50 % of the soil strength. According to the current level of knowledge, this border represents the transition of a soil from completely elastic behaviour to initial plastic deformation of the soil structure: Keller et al. [15] were able to show that a direct transfer of precompression values obtained from laboratory oedometer readings to the strength of soils in the field is not possible.

The border between the yellow and red hazard levels represents a soil stress equal to 110% of the soil strength. Based on recent wheeling test findings, considerable plastic deformation and thus damaging compaction are to be expected in the red zone.

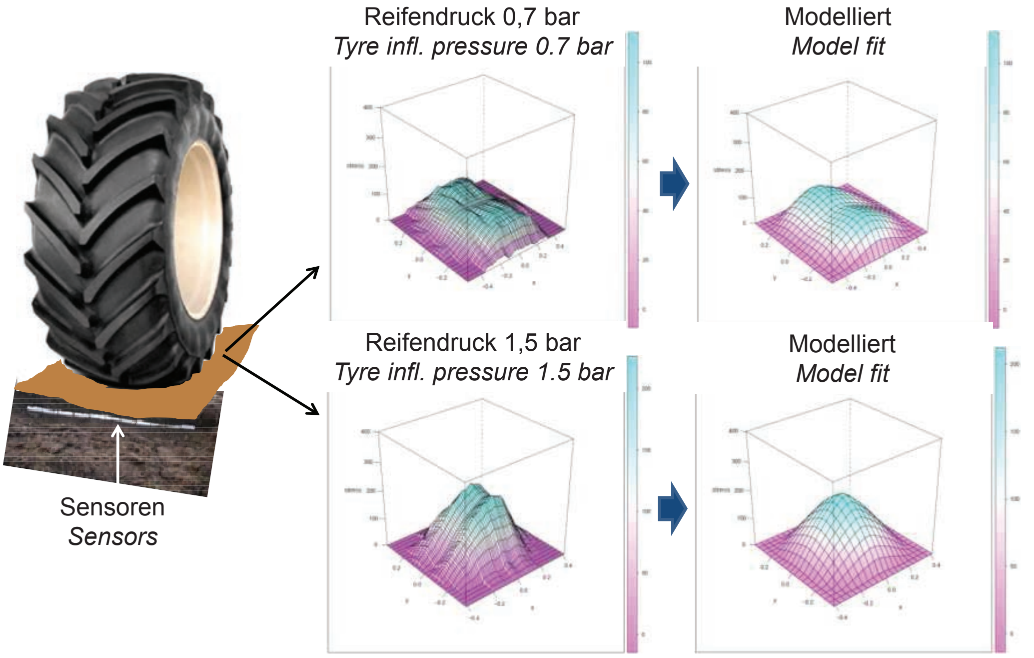
Terranimo® expert: detailed analysis of the physical load applied to the soil

Terranimo® expert is considerably more complex than Terranimo® light. It allows specialists to simulate specific situations of vehicles being driven on the soil. Terranimo® expert is composed of four sub-models:

- Upper model boundary: contact area and stress distribution between the tyre and the soil
- Stress propagation in the soil
- Calculation of soil strength in the soil profile
- Assessment of the compaction risk based on the calculated stress and the actual soil strength

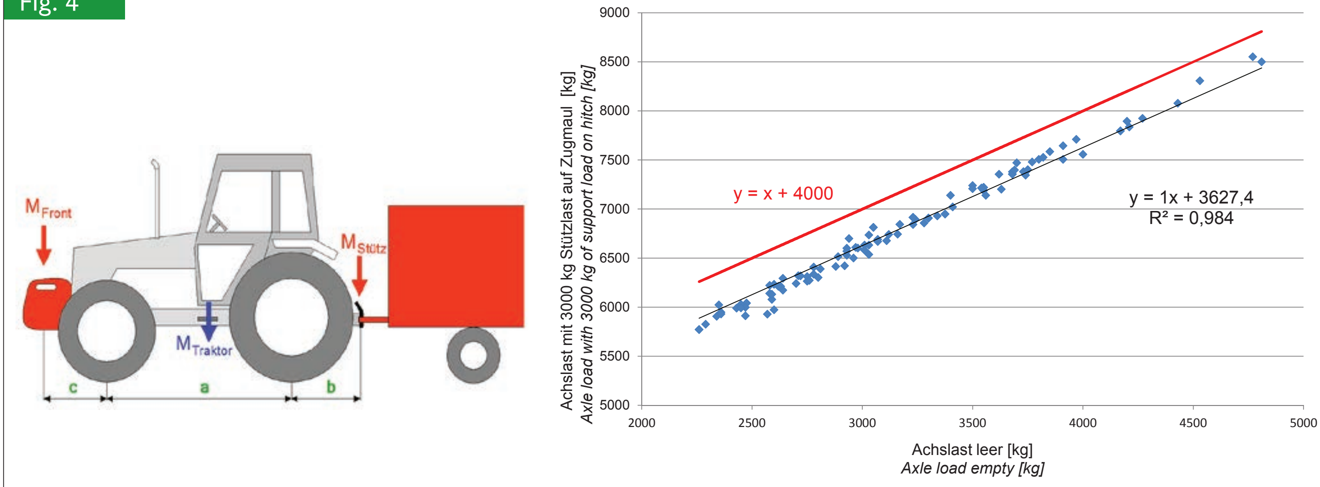
The characterization of the upper model boundary is based on the FRIDA model, which can calculate the contact area and the stress distribution in the tyre-soil interface, which in turn is essential for a realistic simulation of stress distribution in the soil [6; 16; 17; 18]. The outline of the contact area (tyre footprint) is described by a super-ellipse, whereas stress distribution in the direction of movement is modelled by a power function and stress distribution perpendicular to the direction of movement is modelled by an exponential decline function [19; 20; 21]. FRIDA is able to describe the actual conditions very well, in particular the predominant influence of tyre inflation pressure (**Figure 3**).

Fig. 3



Measured (left diagrams) and FRIDA modeled stress states between tyre and soil at different tyre inflation pressures. The example here shows a Michelin 650/65R38 Multibib with 3.5 t wheel load

Fig. 4



Load components and relevant dimensions of a tractor for the determination of axle load transfer (left) (Source: Agroscope), relationship between rear axle load when empty and rear axle load when applying a support load of 3 000 kg of 100 investigated tractors, the red line represents the relationship used in Terranimo® expert (right)

In order to use FRIDA for tyres other than those studied, estimator functions were developed to calculate the various FRIDA model parameters. Accordingly, it is possible to predict the contact area and contact stress relationships for all types of tyres using easily obtainable tyre data (tyre width, tyre diameter, rim diameter, static loaded radius, and the tyre inflation pressure recommended by the manufacturer as well as the actual tyre inflation pressure), the wheel load and the topsoil strength [4; 22].

In order to simplify and speed up the input of tyre data, a databank of commonly used tyre brands and models was added to the model. This databank now contains over 1 000 tyres of the following brands: Alliance, Continental, Goodyear, Kléber, Michelin, Nokian, Trelleborg and Vredestein, listed with all available technical specifications according to ETRTO (European Tyre and Rim Technical Organisation).

Terranimo® expert offers an additional function for calculating the axle load changes on the tractor induced by the hooking up of an implement. Although the latter are not that easy to calculate because of leverage effects and the minimum load on the steering axle prescribed by law (at least 20 % of the total weight must be borne by the steering axle), they are nevertheless indispensable for determining the current wheel load and for correctly calculating soil stress. Considerable load changes are induced on tractor axles specifically by heavy trailers with permissible support loads of 3000 kg (bottom hitching). Because these situations also typically require a front ballast in order to achieve a sufficient load on the front axle, the total weight of the tractor increases to over 3000 kg. In order to model such effects in Terranimo® expert, the data sets of tractor tests conducted in the last 20 years or so by the Swiss research institute Agroscope (at its Tänikon site) were studied [23].

The wheel base, the distance of the drawbar eye from the rear axle and the distance of the centre of gravity of the front ballast from the front axle play a decisive role in the load transfer effect in the horizontal plane. The analysis of the tractor test data showed that the axle load changes in the tested vehicles can be described very well with linear functions. **Figure 4** illustrates the relationship of rear axle loads of 100 tractors (tare weight of 4020 kg to 8130 kg) with and without support loads (3 000 kg), including front ballasting for a 20 % steering axle load. In Terranimo® expert, a slightly higher additional stress was calculated in each case for the rear axle (**Figure 4**, red line), in order to avoid underestimating the loads on the one hand and to account for the additional load transfer effect due to the resistance of the trailer to rolling on the other.

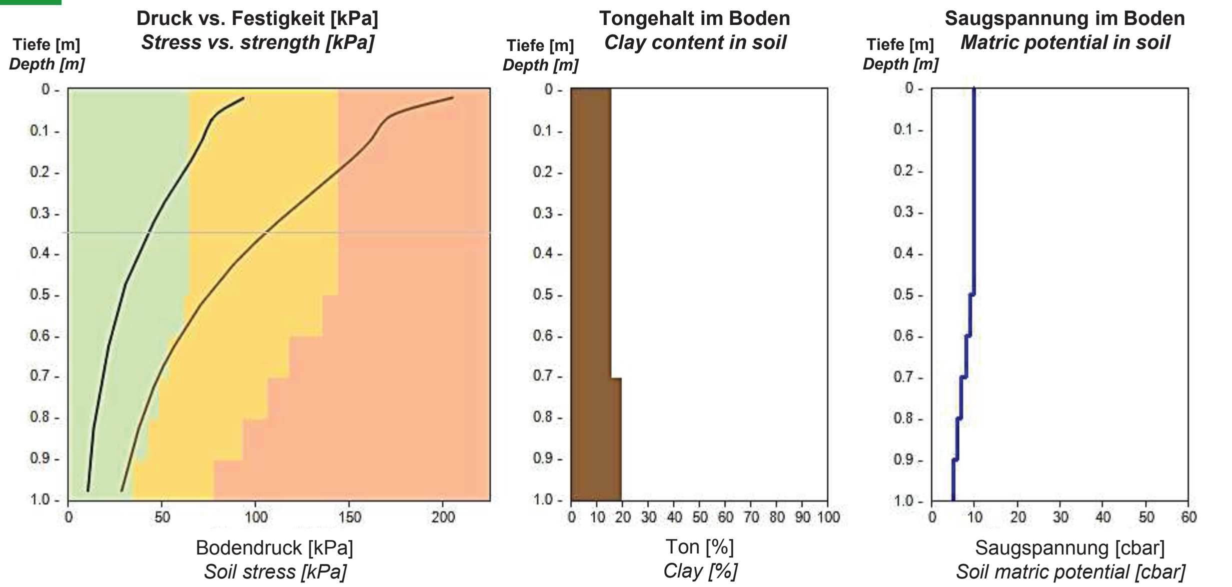
Stress propagation is calculated semi-analytically in Terranimo® expert based on the formulas of Boussinesq [24], Fröhlich [25] and Söhne [16]. A key element of this theory is the concentration factor ν, which determines the pattern of the stress propagation in the soil. In Terranimo® expert, the concentration factor varies in relation to soil strength, as already proposed by Söhne [16]: in soft (wet) soils $\nu = 6$, in hard (dry) soils $\nu = 4$, and in medium (moist) soils $\nu = 5$.

Soil strength in Terranimo® expert is calculated in a similar manner as in Terranimo® light; the risk of compaction is also presented in the form of a three-coloured decision chart. Terranimo® expert, however, offers additional analysis options such as a graph comparing compression stress versus soil strength in all soil layers (**Figure 5**). With such presentations it is possible to assess the compaction risk over the entire soil profile rather than in just the 35 cm Swiss reference depth as in Terranimo® light.

Discussion

With Terranimo®, a simulation model was developed to help farmers decide on the driveability of crop land and use agricultural vehicles in a soil-conserving manner. The strengths of the model lie chiefly in the simulation of stress distribution in the tyre-soil interface, which as the upper boundary has a decisive

Fig. 5



Result plots in Terranimo® expert. Left: soil stress under two different wheels (lines) and soil strength (green, yellow, red) in the soil profile. Middle and right: corresponding clay content, and soil matric potential

influence on stress propagation in the soil [6; 16; 17; 18]. Stress propagation is calculated according to the established method of Söhne [16], but with the difference that instead of the imprecisely defined terms "soft soil" or "hard soil" used by Söhne, the matric potential and the water content of the soil serve as a measure for choosing the concentration factor and hence the stress propagation characteristics.

The principle of precompression stress is used to assess soil strength. This means that only a yes/no statement regarding soil deformation is possible, which suffices to assess the risk of soil compaction. Because Terranimo® does not quantify deformation, however, a continuous change in soil structure (as can occur when, for example, the soil is driven on repeatedly) cannot be simulated. This would require factoring in additional soil mechanics properties (e.g., compression coefficient) that are neither readily available nor easily calculated.

Terranimo® uses clay content and matric potential to calculate precompression stress values. Although the basic data set from Denmark only contained soils with clay contents < 20 %, our analysis of data from the literature [11; 12] shows that the estimator function in Terranimo® also generates acceptable values for heavier soils. We realize, however, that the variation in the measurement values is large and that factoring in other parameters (e.g., bulk density) or soil structure attributes could improve the precision of the estimate. However, it should also be noted that there are no readily available measurements for either bulk density or soil structure attributes.

Conclusions

By linking established findings on stress propagation and soil strength as well as new models for simulating stress distribution between tyres and the soil surface with modern internet technology, it was possible to develop an interesting and user-friendly tool for assessing the risk of soil compaction under agricultural machinery. There are plans to improve Terranimo® on an ongoing basis. Along with updating the data banks (e.g., entry of data on new tyre models) and improving the user interface, there are plans for gradually overcoming the critical points mentioned. A long-term goal is the linkage of Terranimo® with sensor data and with the terminal on the machine. Such an instrument would provide the operator with invaluable information automatically and in real time for optimizing field use.

References

[1] Berisso, F.E. et al. (2012): Persistent effects of subsoil compaction on pore size distribution and gas transport in a loamy soil. Soil & Tillage Research 122, S. 42–51
[2] BAFU und BLW (2013): Bodenschutz in der Landwirtschaft. Ein Modul der Vollzugshilfe Umweltschutz in der Landwirtschaft. Bundesamt für Umwelt, Bern. Umwelt-Vollzug Nr. 1313, www.bafu.admin.ch/uv-1313-d, Zugriff am 15.5.2014
[3] BAFU (2001): Bodenschutz beim Bauen. Leitfaden Umwelt Nr. 10 des Bundesamtes für Umwelt, Bern
[4] Schjønning, P. et al. (2006): Reduction of soil compaction: magnitude and distribution of stress in the contact area between wheel and soil. Report Markbrug No. 127, The Danish Institute of Agricultural Sciences, Tjele, Denmark
[5] Schjønning, P. et al. (2012): Rules of thumb for minimizing subsoil compaction. Soil Use and Management 28(3), pp. 378–393
[6] Keller, T.; Arvidsson, J. (2004): Technical solutions to reduce the risk of subsoil compaction: effects of dual wheels, tandem wheels and tyre inflation pressure on stress propagation in soil. Soil & Tillage Research 79, pp. 171–205
[7] Schjønning, P. (1991): Soil mechanical properties of seven Danish soils. Tidsskrift for Planteavl 95, Report No. S2176, p. 458
[8] Gregory, A.S. et al. (2006): Calculation of the compression index and precompression stress from soil compression test data. Soil & Tillage Research 89, pp. 45–57
[9] Hartge, K.H.; Horn, R. (1984): Untersuchungen zur Gültigkeit des Hooke'schen Gesetzes bei der Setzung von Böden bei wiederholter Belastung. Z. Acker-Pflanzenbau 153, S. 200–207

[10] Schjønning, P. (2011): Multiple regression equation to predict pre-compression stress from clay and pF. Aarhus University, Dänemark, unveröffentlicht
[11] Arvidsson, J.; Keller, T. (2004): Soil precompression stress. I. A survey of Swedish arable soils. Soil & Tillage Research 77, pp. 85–95
[12] Rücknagel, J. et al. (2007): Estimating precompression stress of structured soils on the basis of aggregate density and dry bulk density. Soil Tillage Res. 92, pp. 213–220
[13] Koolen, A. J.; Kuipers, H. (1983): Agricultural Soil Mechanics. Berlin, Springer-Verlag
[14] Cavalieri, K. M.V. et al. (2008): Determination of precompression stress from uniaxial compression tests. Soil & Tillage Research 98, pp. 17–26
[15] Keller, T. et al. (2012): In Situ Subsoil Stress-Strain Behavior in Relation to Soil Precompression Stress. Soil Science 177, pp. 490–497
[16] Söhne, W. (1953): Druckverteilung im Boden und Bodenverformung unter Schlepperreifen. Grundlagen der Landtechnik 5, S. 49–63
[17] Hammel, K. (1994): Soil stress distribution under lugged tires. Soil & Tillage Research 32, pp. 163–181
[18] Keller, T. et al. (2014): Transmission of vertical soil stress under agricultural tyres: Comparing measurements with simulations. Soil & Tillage Research 140, pp. 106–117
[19] Keller, T. (2005): A model for prediction of the contact area and the distribution of vertical stress below agricultural tyres from readily-available tyre parameters. Biosystems Engineering 92, pp. 85–96
[20] Lamandé, M.; Schjønning, P. (2008): The ability of agricultural tyres to distribute the wheel load at the soil–tyre interface. Journal of Terramechanics 45, pp. 109–120
[21] Schjønning, P. et al. (2008): Modelling effects of tyre inflation pressure on the stress distribution near the soil-tyre interface. Biosystems Engineering 99, pp. 119–133
[22] Schjønning, P. et al. (2014): Tyre-soil contact area and distribution of the vertical stress component: predictions based on tyre characteristics. Soil & Tillage Research, eingereicht
[23] Landis, M. (2011): Tabelle mit den Abmessungen der getesteten Traktoren. Forschungsanstalt Agroscope Standort Tänikon, Schweiz. Persönliche Mitteilung. Testberichte abrufbar unter: www.traktorentest.ch, Zugriff am 15.5.2014
[24] Boussinesq, J. (1885): Application des potentiels à l'étude de l'équilibre et du mouvement des solides élastiques. Paris, Gauthier-Villars
[25] Fröhlich, O. K. (1934): Druckverteilung im Baugrunde. Wien, Springer Verlag

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