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Transmission of vertical stress beneath a sandy silt on agricultural fields in Tarabuco: Matric suction effect and comparison of measurements of vertical stress at several tire inflation pressures.

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ABSTRACT

The present paper show measurements and simulations of the increase in vertical stress and matric suction, caused by the passage of agricultural machinery at different conditions of tire inflation pressure. For the field tests, has been chosen three agricultural places located in Tarabuco-Chuquisaca (Bolivia) constituted by a sandy silt (ML). The machinery is an agricultural tractor model John Deere 6110D. It is employed several tire inflation pressures of 83 kPa, 110 kPa, 138 kPa and 193 kPa for the front and rear wheels, in order to analyse their influence on the distribution of vertical stress along the three soil profiles. Increase in vertical stress and matric suction are studied at the three different depths of 0.15 m, 0.30 m and 0.45 m. For the field measurements of increase in vertical stress and matric suction, miniaturized compressive load cells (i.e., 16.5 mm in diameter) and tensiometers (red fill type) were employed respectively. Finally, measurements and simulations of the increase in vertical stress and matric suction were compared between the different tire pressures predetermined. With the results obtained, it was concluded the increase in tire pressure was produced a corresponding increase in vertical stress, as well this variation didn't represent some change in matric suction.

Keywords: Vertical stress, tire pressure, Matric suction, load cells, Red fill tensiometers.

1 INTRODUCTION

Soil compaction is the process by which unsaturated soil porosity is decreased and soil dry density is increased because of agricultural field traffic. Compaction induced soil deformation negatively affects a range of vital soil functions and ecosystem services, such as soil infiltration, the soil filter function, soil aeration and soil–atmosphere gas exchange, biodiversity, and plant growth. Soil compaction has been widely studied, but several aspects of the soil compaction process are still not well understood (Hamza and Anderson, 2005; Chamen et al., 2015; Keller et al., 2016). On the other hand, there are several uncertainties involved in both measuring and simulating soil stress (Keller et. Al., 2016).
In particular, there are more limited documentation regarding the chain of cause and effect for a soil profile in order to reach its plastic state due to the passage of machinery (Lamandé, 2011). An example of this causal chain is the appropriate choice of an inflation pressure for the rear/front tires of a tractor and their effect on the increase in vertical stress, generated in the soil profile (Damme et. al., 2019).

The main purpose of the present paper is to analyse the effect of tire inflation pressure on the increase in vertical stress of three soil profiles, caused by the passage of an agricultural tractor. This operation is managed at several tire inflation pressures, from the one recommended by the manufacturer to the maximum allowed one. The rest of the objectives are to measure increase in vertical stresses in a soil profile at the predetermined depths of 15 cm, 30 cm and 45 cm, below the front and rear tires of an agricultural tractor (is used compression load cells of Italian technology for this field work); to repeat vertical stress measurements at three different predetermined tire inflation pressures, according to their type, applied to the front and rear wheels (is used a portable air compressor, which will allow the variation of tire pressure in the field in every wheeling event); to repeat this wheeling events varying tire inflation pressure, in three soil profiles; to validate measurements of increase in vertical stress, with TERRANIMO software (López, 2020) and the Söhne analytical solution (Söhne, 1958) at the predetermined tire pressures along the three soil profiles; to measure matric suction in each soil profile, at the same depths of analysis as the vertical stresses and for each inflation pressure variation; and to analyse the effect of tire inflation pressure variation on the increase in vertical stresses at the moment of the wheeling events with the agricultural tractor along the three soil profiles.

2 MATERIALS AND METHODS

2.1 Experimental site, machinery properties

The three field test sites are the soil profile S1 (19°10’17.88” S, 64°53’54.28” W), S2 (19°10’15.94” S, 64°53’52.69” W) and S3 (19°10’5.65” S, 64°53’52.69” W), all located in Tarabuco, Chuquisaca (Figure 1).

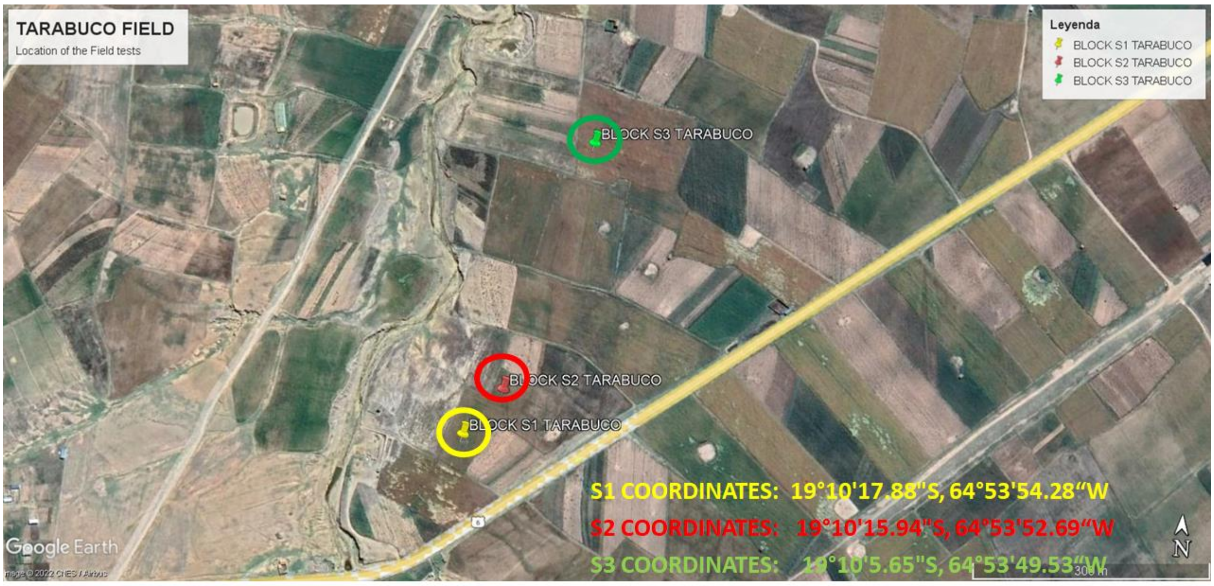


Figure 1. *Location of the field test (yellow circle S1, red S2 and green S3).*

The three soil profiles are constituted by a silty sand with low plasticity (ML), according to USCS classification. In table 1 are presented a resume of the characterization data.

Table 1. *Soil characterization.*

Soil Profile	Clay %	Silt %	Sand %	ρ_0 (g/cm^3)	Gs	USCS	Organic (%)
S1	8	48	44	1.70	2.64	ML	0.52
S2	10	52	38	1.72	2.65	ML	0.45
S3	8	50	42	1.67	2.65	ML	0.55

Machinery employed during the field tests is a JOHN DEERE agricultural tractor model 6110 D with a tire type 13.6R24 in the front Wheel, and type 18.4R34 in the rear Wheel. For both tires, tire pressure has been ranged from the 83 kPa recommended by the manufacturer (DEERE & COMPANY, 2008) until maximum allowed. Table 2 present the several tire pressures managed in both wheels.

Care was taken in order to not exceed the maximum tire pressure allowed by the manufacturer (Firestone, 2020). That is the reason for range the tire pressure from the recommended to the maximum one with an additional intermediate.

***Table 2.** Tire pressure variation.*

Tire type/model	Tire inflation pressures		
	recommended (kPa)	intermediate (kPa)	maximum (kPa)
13.6R24	83	138	193
18.4R34	83	110	138

2.2 Measurements of vertical stress increase.

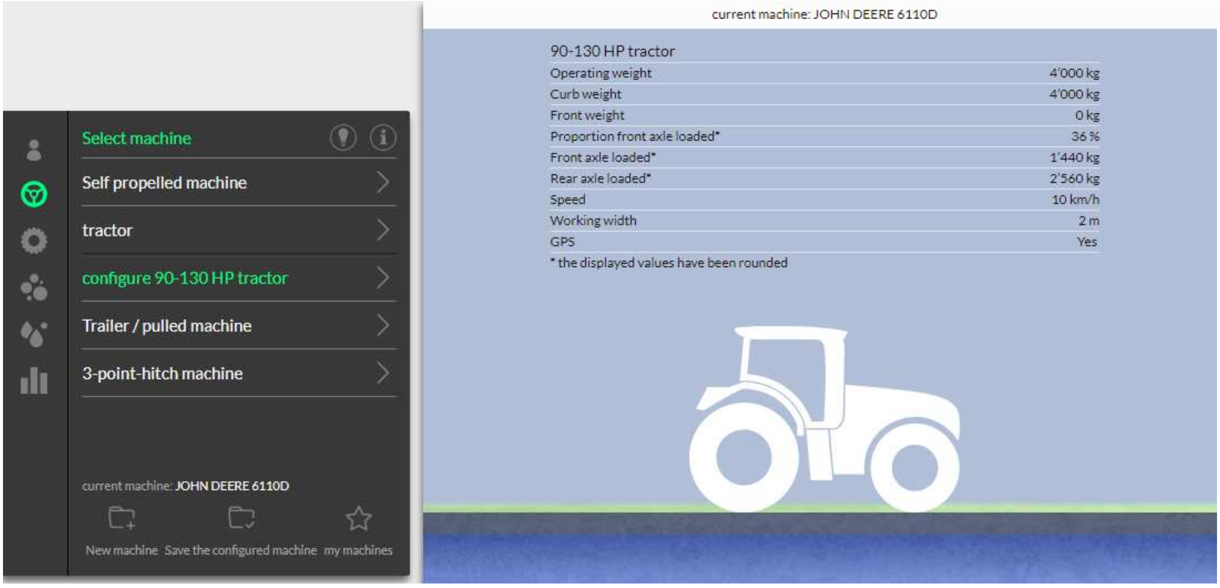
For this purpose, it was used miniature compression load cells (S2 Tech BC-302 as described in Torrico et. al., 2020), which were installed at the depths of 15 cm, 30 cm and 45 cm. Care was taken in order to keep all the load cells in the middle of the wheeling pass path and the most closely to the red fill tensiometers. In the present work it was only considered relative changes in vertical stress between each tire pressure; the actual earth pressure measurement is much more complex.

Tire inflation pressure variation is measure with a portable air compressor along the six predetermined variations in the rear and front Wheel of the John Deere 6110 D tractor. In every wheeling event, it was measured the contact area between tire and soil with paper sheets.

2.3 Simulation of Vertical stress increase

In order to validate measurements of vertical stress registered along the several wheeling events conducted at the predetermined tire pressures in the three field experimentation sites, at was employed analytic simulations with Terranimo software (López, 2020) and the Söhne model (Söhne, 1958).

Terranimo is a free Access software (www.terranimo.world), which evaluate the possible risk of soil compaction due to the pass of an agricultural machinery. The software employ input data such as soil texture, organic matter, dry density and matric suction (figure 2). This is the reason why the matric suction monitoring was conducted around the three filed sites.



current machine: JOHN DEERE 6110D

90-130 HP tractor

Operating weight	4'000 kg
Curb weight	4'000 kg
Front weight	0 kg
Proportion front axle loaded*	36 %
Front axle loaded*	1'440 kg
Rear axle loaded*	2'560 kg
Speed	10 km/h
Working width	2 m
GPS	Yes

* the displayed values have been rounded

current machine: JOHN DEERE 6110D

***Figure 2.** Software Terranimo with machinery properties.*

$$\sigma_z = \sum_{i=}^{i=n} (\sigma_z)_i = \sum_{i=0}^{i=n} \frac{\upsilon P_i}{2\pi z_i^2} cos^{\upsilon+2}\theta_i \qquad Eqn(1)$$

Equation 1 correspond to the analytic model of Söhne. For more details of this equation, please refer to Torrico et. al., 2020.

2.4 Matric Suction monitoring

Red fill tensiometers (Torrico et. al., 2020) have been installed in the field tests with the major proximity to the load cells. The main purpose is to obtain the most representative value of matric suction at the moment of the wheeling event in every tire inflation pressure variation at the three different depths predetermined of 15 cm, 30 cm and 45 cm. Matric suction values in the field have been registered once at day (Torrico et. al., 2021).

2.5 Procedure for the field tests

Lamandé et. al. (2011) established the procedure the install load cells in the field. According Lamandé, load cells housings were built in order to protect the load cells from the soil at the moment of the laterally insertion. Load cells housings (30 mm width, 20 mm height and 60 mm length) has an empty space for the exactly accommodation of every load cell (16.5 mm diameter and 5 mm height); just the above part of the load cell is keeping in touch with the surrounding soil (Lamandé et. al., 2015). Load cells housings prevent a possible damage in the load cells (Lamandé et. al., 2011). Figure 3 shows these manufactured devices.

Figure 3. *Load cells housings (left). Red Fill tensiometers installation and load cells laterally insertion at the predetermined depths of 15 cm, 30 cm and 45 cm.*

In total, nine soil tests were conducted along the three field tests (S1, S2, S3), with whom were conducted fifty-four measurements of increase in vertical stress and nine matric suction measurements at the different pre-determined depths and specified tire inflation pressures.

3 RESULTS

3.1 Measurement and validation of vertical stress increase in the three soil profiles

Figures 4 show results of vertical stress increase obtained in the field site S1, with the tire inflation pressure variations imposed in table 2. Results correspond to measurements with load cells, simulations with Terranimo software (López, 2020) and Söhne Analytical model (Söhne, 1958). For the next figures and tables, we will reference as “FW” to the front wheel, “RW” to the rear wheel, “83 83” to the test conducted at the recommended tire pressures (the first number correspond to the front wheel tire pressure), “138 110” to the tests conducted at the intermediate tire pressures and “193 138” to the soil tests conducted at the maximum allowed tire pressures.

Results obtained, which are showing in figures 4 demonstrate a correlation between measurements and simulations; however, it was encountered a certain overestimation of load cells measurements compared with simulations at the three different depths for both rear axle and front axle. Besides, at the depth of 15 cm, this overestimation is more pronounced with regard to simulations with Terranimo and Söhne analytical solution; meanwhile, at the depths of 30 cm and 45 cm, the overestimation of the load cells measurements is more close to them.

Comparison between simulation results of Söhne model and Terranimo software, the difference is reduced at the depths of 30 cm and 45 cm. However, at the depth of 15 cm the difference is major as we can see in figure 4.

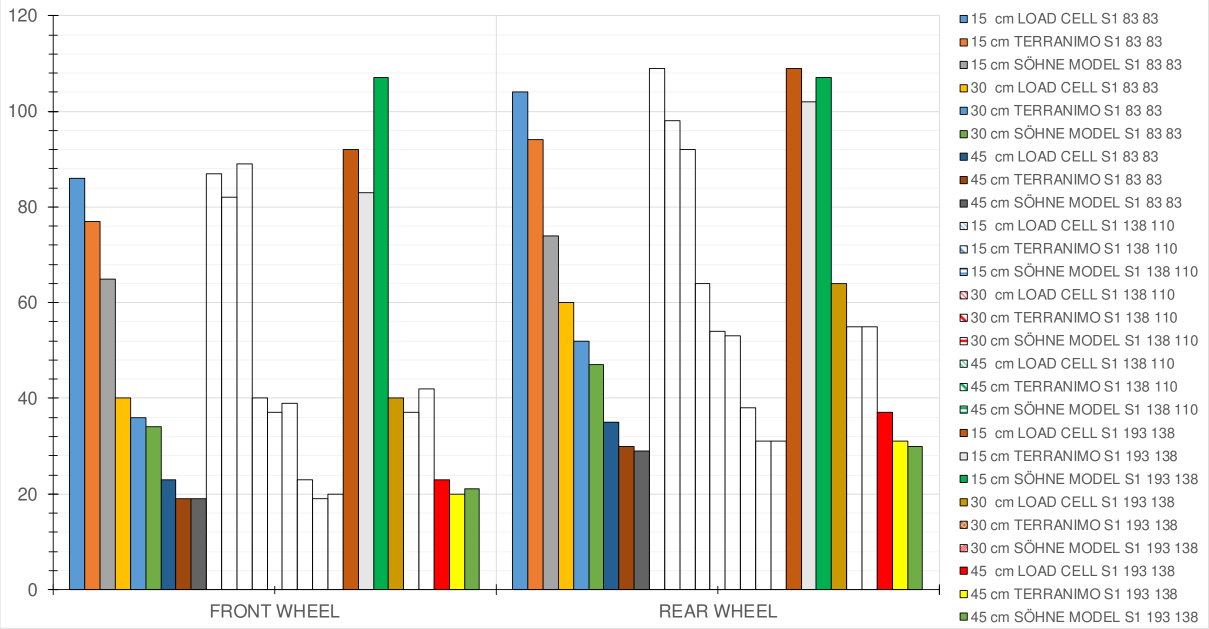


Figure 4. *Soil S1. Vertical stress increase variation for the rear and front wheels, at the predetermined tire pressures. Comparison between measurements (LOAD CELL) and simulations (TERRANIMO AND SÖHNE).*

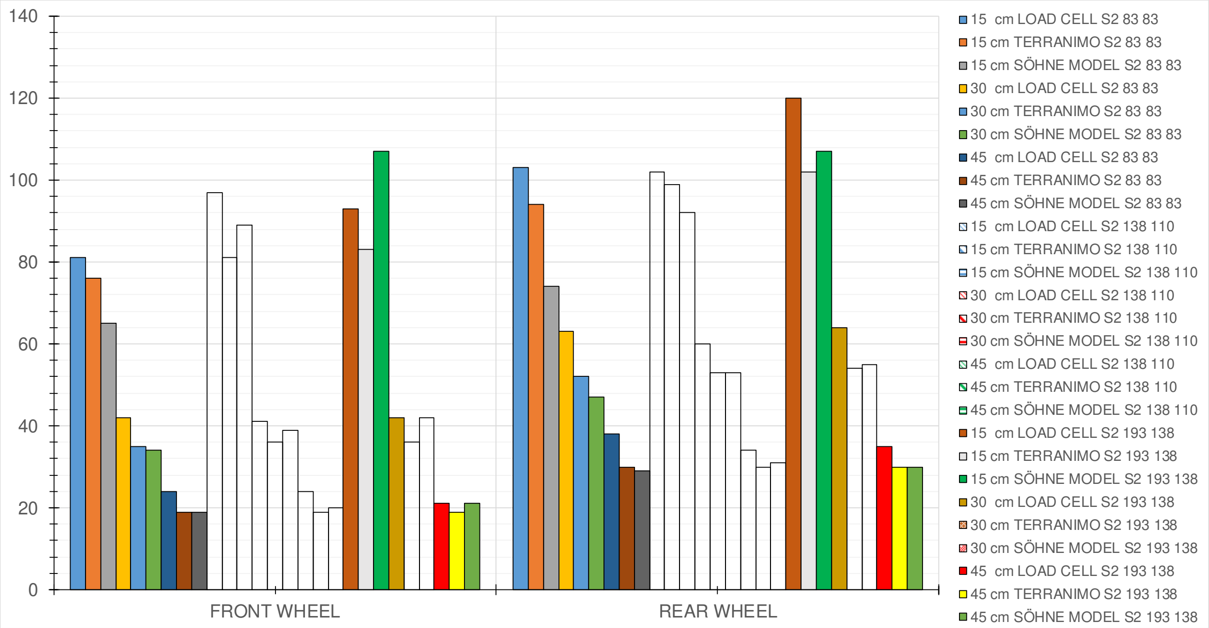


Figure 5. *Soil S2. Vertical stress increase variation for the rear and front wheels, at the predetermined tire pressures. Comparison between measurements (LOAD CELL) and simulations (TERRANIMO AND SÖHNE).*

Figures 5 show vertical stresses obtained in the soil profile S2 with the tire pressures predetermined in table 2. It was obtained similar results at the soil profile S1 and besides, it was confirmed a correlation between load cells measurements, the analytic solution of Söhne and the simulation with Terranimo. Comparing results, in almost all the cases exists the same behaviour as profile S1 field tests, i.e., load cells measurements results conducted to overestimated values against analytical solutions (Söhne, 1958) and Terranimo software simulations. At the depth of 15 cm is where the difference between measurements, analytical solution and simulations have the major value for both wheels (front and rear). At the depth of 30 cm and 45 cm, this difference reduces.

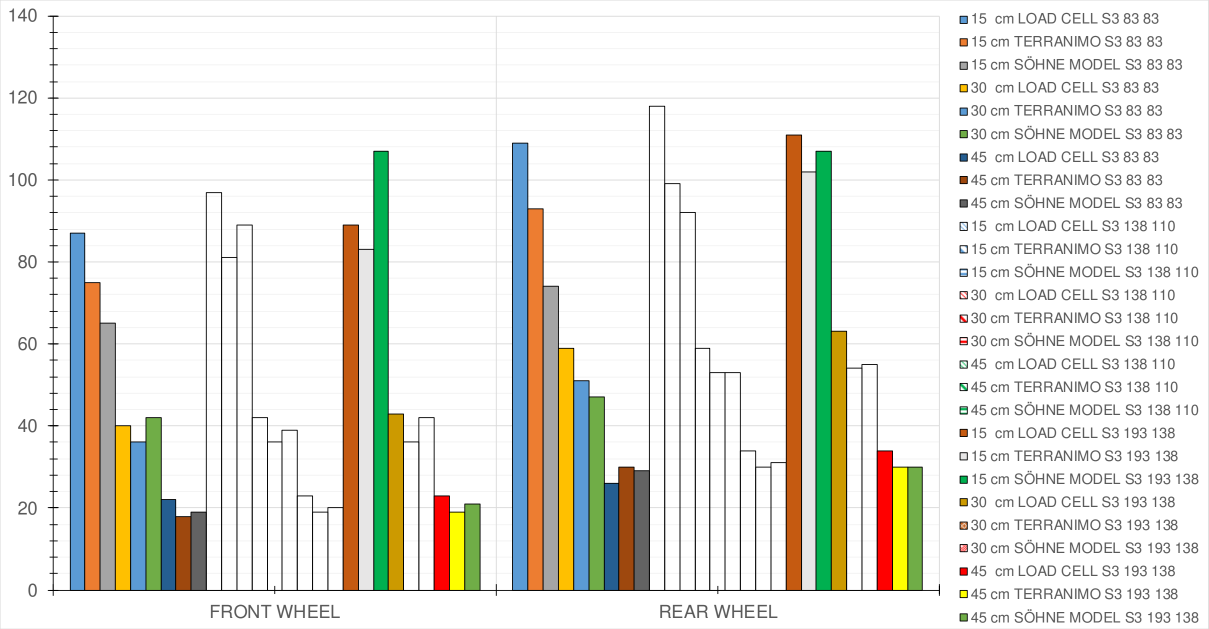


Figure 6. *Soil S3. Vertical stress increase variation for the rear and front wheels, at the predetermined tire pressures. Comparison between measurements (LOAD CELL) and simulations (TERRANIMO AND SÖHNE).*

Figures 6 show results obtained around the field test S3, with the tire inflation pressures imposed in table 2. These results are similar to Field tests S1 and S2 in order to compare values of vertical stress increase, correlation between measurements and simulations, and the depth of major deviation (15 cm). Therefore, around the nine field tests conducted in the three soil profiles (S1, S2 and S3) it was achieved a repetitiveness of the results, obtained for each soil profile with the agricultural machinery model John Deere 6110 D. In other words, results obtained in soil profile S1 are similar to soil profiles S2 and S3.

3.2 Matric suction measurements

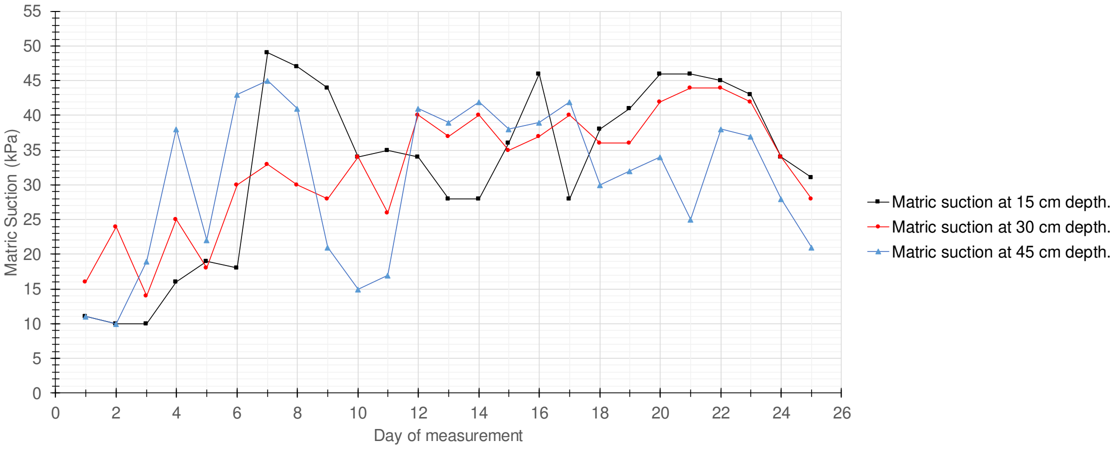


Figure 7. Soil S1, Matric Suction monitoring with red fill tensiometers at 15 cm, 30 cm and 45 cm depth.

For every soil profile analysed (S1, S2 and S3), it was monitored the matric suction at the depths of 15 cm, 30 cm and 45 cm. The monitoring was developed every day without breaks and at the same time (mid-day). Figures 7, 8 and 9 describes the results of the field monitoring. It is important noticed that, at the moment of the wheeling events, in every tire pressure variation imposed with the handle air compressor (Table 2), matric suction remains constant at the moment of the machinery pass around the three specified depths.

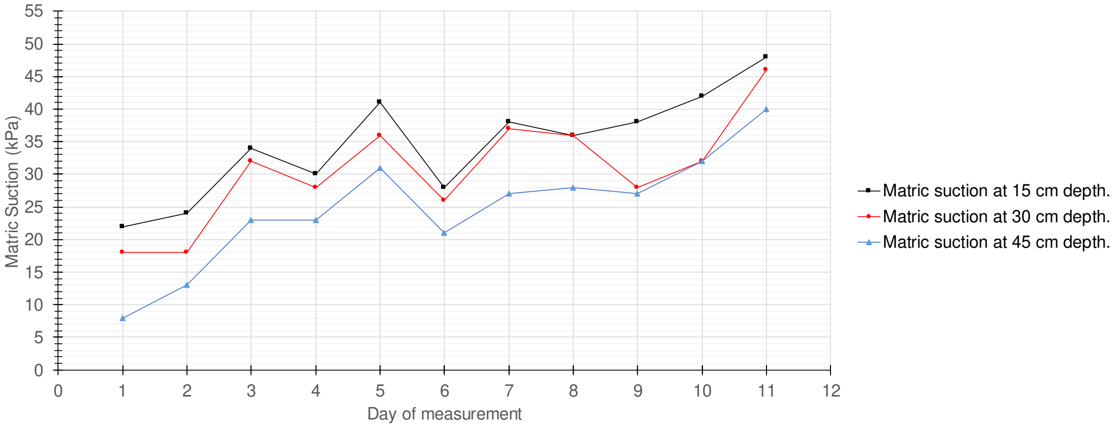


Figure 8. Soil S2, Matric suction monitoring with red fill tensiometers at 15 cm, 30 cm and 45 cm depth.

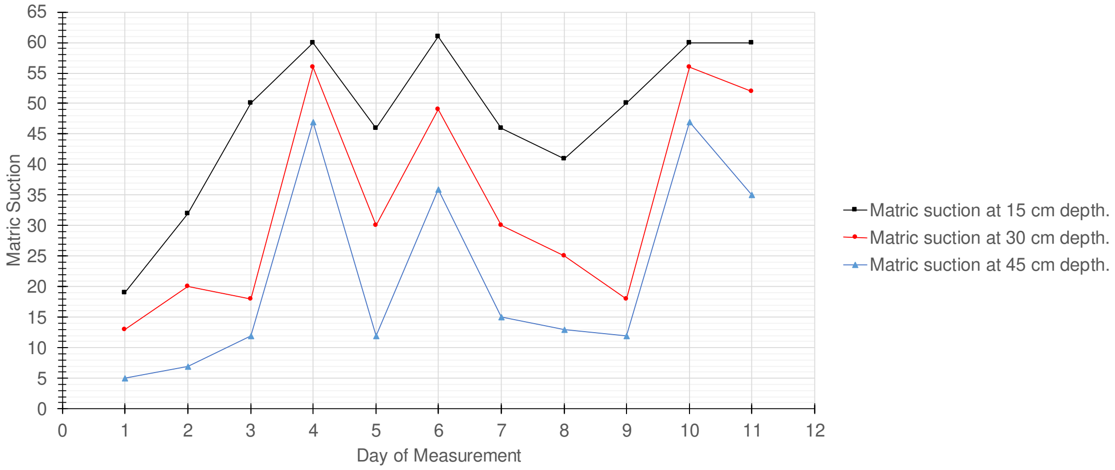


Figure 9. Soil S3. Matric suction monitoring with red fill tensiometers at 15 cm, 30 cm and 45 cm depth.

Table 3 provides the matric suction values registered at the moment of the wheeling events around the three soil profiles. These results were extracted from figures 7, 8 and 9, according to the day of the field test conducted with the agricultural machinery.

Table 3. *Matric Suction values registered along the wheeling events with the agricultural machinery model John Deere 6110 D.*

Soil Profile test	**Matric suction (kPa) per depth**		
	15 cm	**30 cm**	**45 cm**
S1	38	33	30
S2	48	43	40
S3	60	52	35

Table 3 shows that there is a matric suction variation between the wheeling events S1, S2, S3 for the same depth. Specially, at 15 cm depth matric suction increases in 22 kPa from the soil test S1 to S3. However, figure 13 will clarify that these variations don’t represent any effect on the vertical stress increase. All these results registered and showed in tables 1, 2 and 3 were employed usefully as input data for the simulations in software Terranimo in order to obtain vertical stress increase results throughout all the nine field tests, which were showed from figures 4 to 6.

3.3 Tire pressure effect on the vertical stress increase

In order to achieve the main purpose of the present research, the following action have been carried out: Between measurements and simulations, there are available three vertical stress values for one result; therefore, in order to analyse vertical stress behaviour with tire pressure variation, it was used the average between these three values (load cell, Terranimo and Söhne model) per every predetermined depth, wheel type and variation of tire pressure. Tables 4, 5 and 6 summarize per depth, the results of vertical stress increase, according the three soil profiles, the two tire types and the six tire inflation pressures employed in the present research.

Table 4. *Tire inflation pressure effect on vertical stress increase (σ_v) at 15 cm depth.*

Tire pressure applied (kPa)		**15 cm depth**					
		σ_v (kPa) Rear wheel			**σ_v (kPa) Front wheel**		
Rear wheel	**Front wheel**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
83	83	91	90	92	76	74	76
110	138	100	98	103	86	89	89
138	193	106	110	107	94	94	93

Separate the results per depth in tables 4, 5 and 6 have been defined because it is more clearly to notice how the vertical stress increase as the tire inflation pressure has risen, especially at 15 cm depth (table 4), where the increase in tire pressure, from the recommended (83 kPa) to the maximum allowed (138 and 193 kPa), produced an increase in vertical stress up to a maximum of 20 kPa (in the soil profile S2 field test), which means a 22 % increment of vertical stress with regard to the vertical stress registered at the recommended tire pressure, as we can see in table 4.

Table 5. *Tire inflation pressure effect on vertical stress increase (σ_v) at 30 cm depth.*

Tire pressure applied (kPa)		**30 cm depth**					
		σ_v (kPa) Rear wheel			**σ_v (kPa) Rear wheel**		
Rear wheel	**Front wheel**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
83	83	53	54	52	37	37	39
110	138	57	55	55	39	39	39
138	193	58	58	57	40	40	40

Table 6. *Tire inflation pressure effect on vertical stress increase (σ_v) at 45 cm depth.*

Tire pressure applied (kPa)		**45 cm depth**					
		σ_v (kPa) Rear wheel			**σ_v (kPa) Rear wheel**		
Rear wheel	**Front wheel**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
83	83	31	32	28	20	21	20
110	138	33	32	32	21	21	21
138	193	33	32	31	21	20	21

Tables 5 and 6 results demonstrate a similar behaviour as table 4 in terms of vertical stress increase. However, at the depths of 30 cm and 45 cm, the percentage rate is lower than the depth of 15 cm; it was registered a maximum increase of 5 kPa (soil profiles S1 and S3) at the depth of 30 cm, and 3 kPa (soil profile S3) at the depth of 45 cm; which means a vertical stress increase of 9 % and 11 % respectively, with respect to the vertical stress at the recommended pressure.

Finally, figures 10, 11, 12 and 13 show graphically how tire inflation pressure has an effect on the vertical stress increase, along the three soil profiles tested at the three predetermined depths of 15 cm, 30 cm and 45 cm.

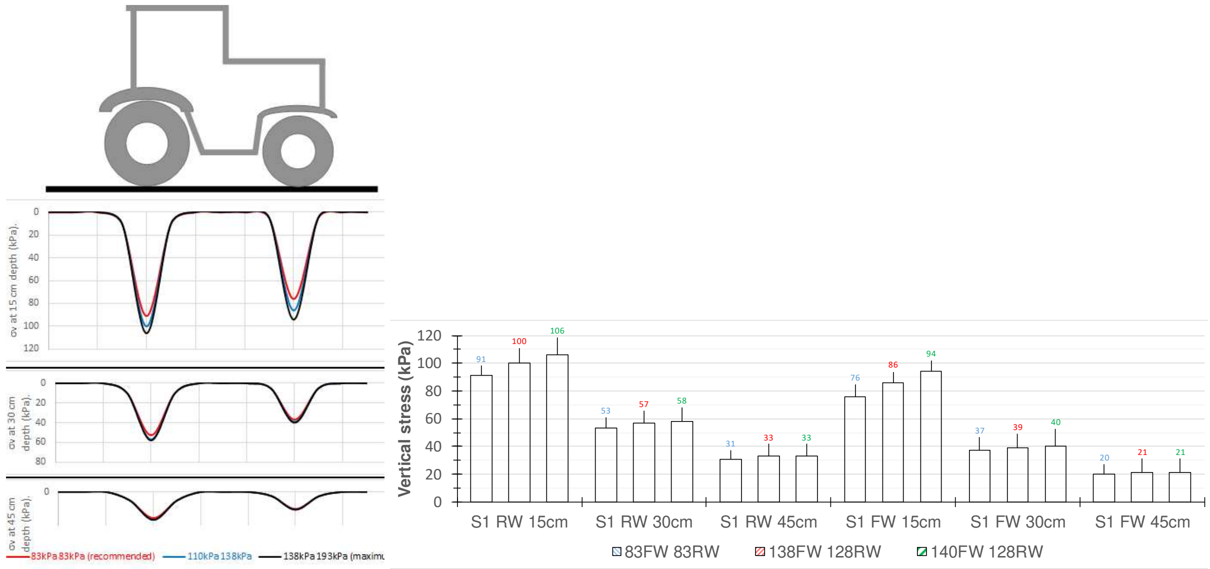


Figure 10. Soil S1, Tire inflation pressure effect on vertical stress increase (σv). Recommended pressure (red line), intermediate pressure (blue) and maximum pressure (black) (left). Bar graph (right)

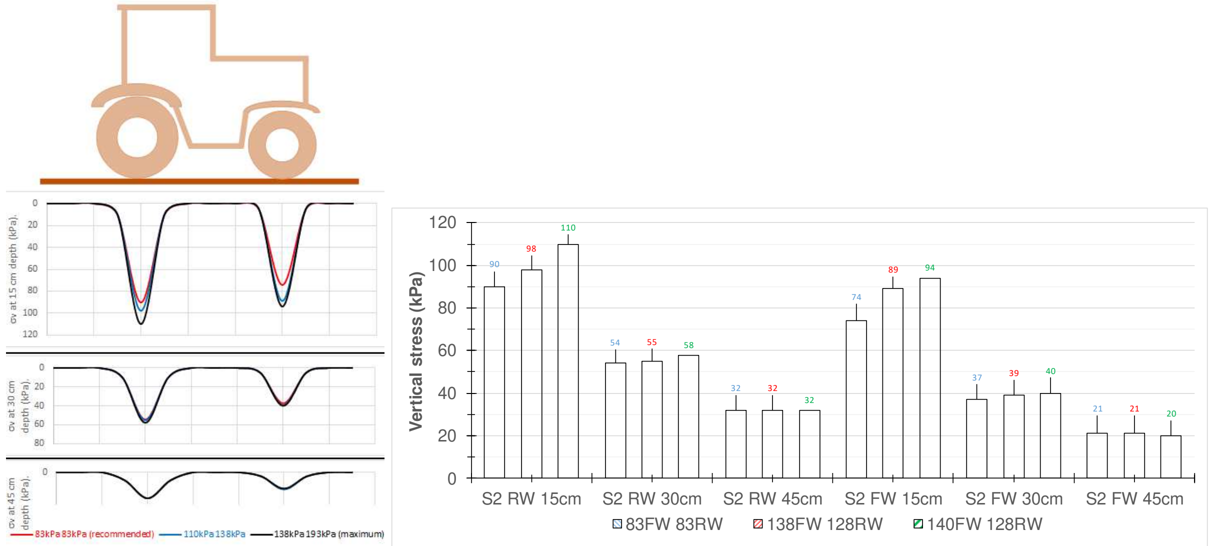


Figure 11. Soil S2, Tire inflation pressure effect on vertical stress increase (σv) (left). Bar graph (right)

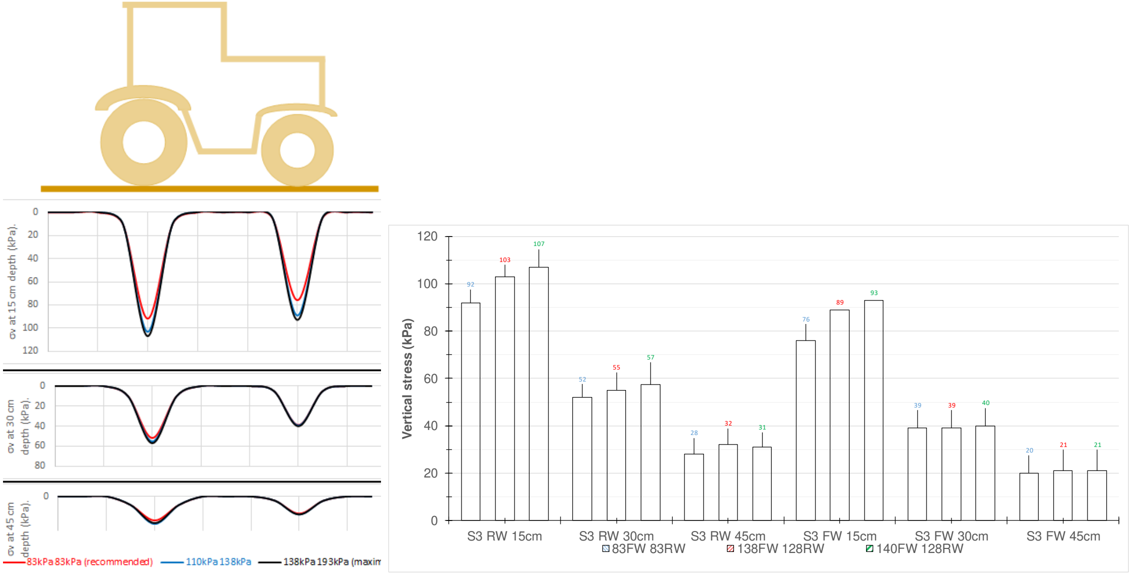


Figure 12. Soil S3, Tire inflation pressure effect on vertical stress (σv) (left). Bar graph (right)

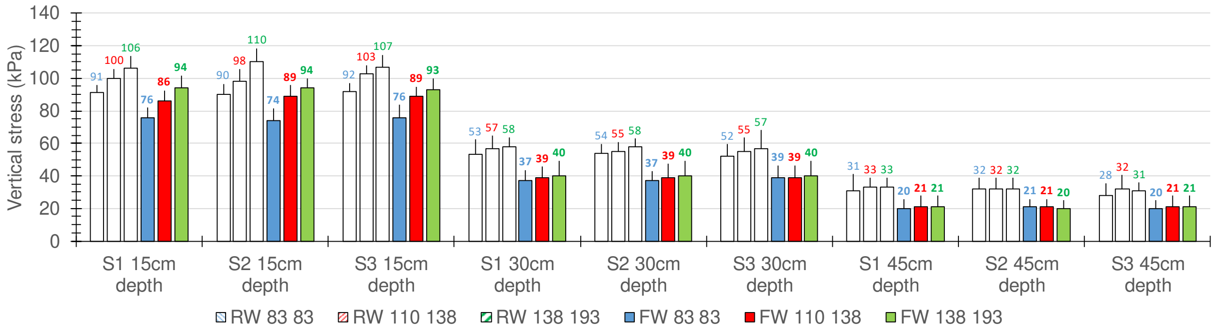


Figure 13. Soil S1, S2, S3 Tire inflation pressure effect on vertical stress (σ_v).

Figure 19 clarify the increase in vertical stress due to increase tire pressure for both rear wheels (oblique lines) and front wheels (filled lines); e.g. for the depth at 15 cm this increase is more notorious for both wheels and along the three soil tests, meanwhile at the depths of 30 cm and 45 cm the increase reduced substantially.

4 CONCLUSIONS

This research concludes that, there is an effect of the tire inflation pressure on the vertical stress increase, particularly at 15 cm depth. With the correspondent increase in tire pressure, it was generated a respectively increase on the vertical stress at the three predetermined depths of 15 cm, 30 cm and 45 cm.

The matric suction variation, registered per depth along the three wheeling events, doesn´t represent any effect to the increase in vertical stress. All the wheeling events were conducted in dry conditions.

The maximum increase of vertical stress registered, due to tire inflation pressure variation, was 22 % at 15 cm depth. Increase of vertical stress at the depths of 30 cm and 45 cm was lesser than 15 cm depth, reaching a value of 9 % and 11 % of increase respectively.

Comparing vertical stress increase measurements with load cells, simulations obtained with Terranimo Software and Söhne analytical solution, there is a correlation and we can see a decrease of vertical stress as major depth of analysis.

Along almost the cases, load cells measurements conducted to the highest values against simulation results and analytical solutions. The maximum load cell measurement overestimation registered was 18.5 % in the soil profile S3. This overestimation in load cells measurements could be attributed to the high stiffness of the load cell housing, which was constructed of steel.

Results obtained in every one of the three soil profiles tested, at the six tire inflation pressures predetermined (along front and rear Wheel) and along the three specified depths, provided similar outcomes of vertical stress increase. Therefore, it was generated a repeatability of the results.

For future research, according with our experimental design, it was scheduled to make the same soil testing program in saturated conditions, that's it in a rainy period. Besides, it was scheduled to conduct precompression stress throughout the three soil profiles, in order to compare results with Terranimo Software and check if the soil remains in their elastic state after the wheeling events along the three specified depths.

5 ACKNOWLEDGEMENTS

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REFERENCES

Chamen, W.C.T., A.P. Moxey, W. Towers, B. Balana, and P.D. Hallett. 2015. Mitigating arable soil compaction: A review and analysis of available cost and benefit data. Soil Tillage Res. 146:10–25. doi:10.1016/j.still.2014.09.011

Damme, L., Stettler, M., Pinet, F., Vervaet, P., Keller, T., Mounkholm, L., and Lamandé, M. (2019). The contribution of the tyre evolution to the reduction of soil compaction risks. Soil Till. Res. 194, 104283, doi: 10.1016/j.still.2019.05.029.

DEERE & COMPANY. (2008). Manual del operador tractors 6100D, 6110D, 6115D, 6125D, 6130D y 6140D Edición H8 (español). Industrias John Deere S.A. de C.V. A John Deere ILLUSTRUCTION Manual.

FIRESTONE AGRICULTURAL & TRACTOR TIRES. (2020). Load and inflation. FirestoneAg.com.

Keller, T., Ruiz, S., Stettler, M., Berli, M. (2016). Determining soil stress beneath a Tire: Measurements and Simulations. Soil Science Society of America Journal 80: 541-553

Lamandé, M., and Schj□nning, P. (2011). Transmission of vertical stress in a real soil profile. Part I: Site description, evaluation of the Söhne model, and the effect of topsoil tillage. Soil Till. Res. 114, 57-70, doi: 10.1016/j.still.2011.05.004.

Hamza, M.A., and W.K. Anderson. 2005. Soil compaction in cropping systems: A review of nature, causes and possible solutions. Soil Tillage Res. 82:121–145. doi:10.1016/j.still.2004.08.009

Torrico, J.A., Miranda, S., Cornellis, W., Rojas, J.C., Di Emidio, G., & Bezuijen, A. (2021). Matric suction effect on distribution of stresses caused by vehicle wheels on a bare silty sand. PanAm-Unsat 2021: 3rd Pan-American Conference on Unsaturated Soils. 337, 03004. https://doi.org/10.1051/matecconf/202133703004

Torrico, J.A., Miranda, S., Cornellis, W., Rojas, J.C., Di Emidio, G., & Bezuijen, A. (2020). Medición del incremento de esfuerzos verticales generados por un vehículo en una arena limosa. Ingenium. 1, 123-128

López, R. (2020). Prevention of soil compaction by agricultural operations: a geotechnical perspective. Master Thesis. Ghent University, Faculty of Engineering and Architecture. Ghent, Belgium.

Söhne, W. (1958). Fundamentals of pressure distribution and soil compaction under tractor tyres. Agricultural Engineering. 39, 276-281 290.

Torrico, J.A., Miranda, S., Cornellis, W., Rojas, J.C., Di Emidio, G., & Bezuijen, A. (2021). Efecto de la succión matricial en la distribución de esfuerzos verticales generados por el paso de un vehículo en una arena limosa bajo diferentes condiciones ambientales. Ingenium. 2, 15-21.

Lamandé, M., Keller, T., Berisso, F., Stettler, M., and Schj□nning, P. (2015). Accuracy of soil stress measurements as affected by transducer dimensions and shape. Soil Till. Res. 145, 72-77, doi: 10.1016/j.still.2014.08.011.

Das, B. M. (2013). Fundamentals of Geotechnical Engineering 4th Edition. Cengage Learning. ISBN 978-1-111-5765-2.

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