AgriEngineering

Article

Straw Cover and Tire Model Effect on Soil Stress

Aldir Carpes Marques Filho [1,*], Lucas Santos Santana [2], Murilo Battistuzzi Martins [3], Wellingthon da Silva Guimarães Júnnyor [3], Simone Daniela Sartório de Medeiros [4] and Kléber Pereira Lanças [5]

[1] Agricultural Engineering Department, Federal University of Lavras (UFLA), Lavras 37200-900, Brazil
[2] Institute of Agricultural Sciences, Federal University of Jequitinhonha and Mucuri Valleys (UFVJM), Av. Universitária, Unaí 38610-000, Brazil; santana.santos@ufvjm.edu.br
[3] Cassilândia University Unit, Mato Grosso do Sul State University (UEMS), 306 Road, Km 6, Cassilândia 79540-000, Brazil; murilo.martins@uems.br (M.B.M.); wellingthon.junnyor@uems.br (W.d.S.G.J.)
[4] Statistical Department, College of Exact Sciences, Santa Catarina Federal University—UFSC, Florianópolis 88034-001, Brazil; sisartorio@ufsc.br
[5] Rural Engineering and Agricultural Mechanization Department, College of Agricultural Sciences, São Paulo State University—UNESP, Botucatu 18610-034, Brazil; kp.lancas@unesp.br
* Correspondence: aldir@ufla.br

Abstract

Heavy machinery degrades agricultural soils, with severity influenced by wheel type, contact area, and soil moisture. Tropical agriculture is characterized by the constant maintenance of straw on the ground. This permanent cover, among other benefits, can mitigate the stress imposed by wheels on the physical structure of the soil. This study aimed to evaluate the effect of tire types and straw amounts on soil stresses. Static studies were carried out under controlled conditions in a static tire test unit (STTU), equipped with standardized sensors and systems that simulated real farming conditions. Three tire models were tested: road truck double wheelset—2 × 275/80R22.5 (p1); agricultural radial tire—600/50R22.5 (p2); and bias-ply tire—600/50-22.5 (p3) on four contact surfaces (rigid surface; bare soil; soil with 15 and 30 Mg ha^{-1} straw cover). We performed comparative statistical tests and subsurface stress simulations for each tire and surface condition. On the hard surface, the contact areas were 4.7 to 6.8 times smaller than on bare soil. Straw increased the tire's contact area, reducing compaction and subsoil stresses. Highest pressure was imposed by the road tire (p1) and lowest by the radial tire (p2). Adding 15 Mg ha^{-1} of straw reduced soil SPR by 18%, while increasing it to 30 Mg ha^{-1} led to an additional 8% reduction. Tire selection and effective straw management improve soil conservation and agriculture sustainability.

Keywords: tire test; soil conservation; mechanization; straw management; bias ply; machine–soil interaction

Academic Editor: Pablo Martín-Ramos

Received: 9 June 2025
Revised: 16 July 2025
Accepted: 11 August 2025
Published: 13 August 2025

Citation: Marques Filho, A.C.; Santana, L.S.; Martins, M.B.; Guimarães Júnnyor, W.d.S.; Medeiros, S.D.S.d.; Lanças, K.P. Straw Cover and Tire Model Effect on Soil Stress. *AgriEngineering* **2025**, 7, 263. https://doi.org/10.3390/agriengineering7080263

1. Introduction

Brazil is one of the largest food-producing countries in the world. However, mechanized operations cause soil degradation and surface compaction [1,2], mainly because machines have become larger and heavier over the years [3].

In tropical agriculture, many challenges are imposed on producers, including preserving the soil structure and maintaining permanent straw cover on the soil [4]. This maintenance of soil cover provides benefits for the crop such as attenuating the soil temperature gradient, maintaining moisture in the root zone, increasing microbiota, etc. However, it can also mitigate the impact of the wheels on the soil, with a physical cushioning effect and by increasing the contact area [4–6].

The tires and wheels of agricultural machinery have the function of supporting and transferring the load to the soil [5]; these are the contact elements that determine traction, work capacity and traffic efficiency. In addition to the amount of straw on the soil surface, the types of tires are decisive in the application of loads to the soil and its level of compaction [6–8].

The tires' characteristics directly influence the traction capacity of machines, fuel consumption and soil compaction. Research on the impact of wheels on the ground and assessments in a controlled environment allows applied mathematical prediction modeling and assessments to be carried out [9–11] and the traction performance to be evaluated [6,12].

Applications and modeling in systems such as TASC, tires/tracks and soil compaction [9], developed in Microsoft Excel, enable assessment of the risk of severe damage to the subsoil. This system considers soil characteristics (such as texture, penetration resistance, and maximum preparation depth) and machine parameters (such as wheel load, tire size, and inflation pressure) to predict compaction risks.

Cargo tires, widely used in transport vehicles in harvesting operations, are relevant in determining the sustainability of agricultural models, as they can increase costs and impact soils, reducing crop productivity over the years. Recently, new tire models have been applied in agriculture, such as road (truck) and industrial (construction machinery) tires. Considering the different agricultural scenarios and the versatility that machines must have to meet these challenges, such as driving within crops and then entering a highway at high speed, highway tires have been gradually used in field operations. The effects on tropical soils are not yet fully known. These non-agricultural tire models have a high capacity to damage the soil and cause compaction [10,13].

Tire models and designs can determine the performance of machines [1], based on the specific claw area or lug area and the total area imprinted on deformable soil. Thus, on hard soils, the real contact area is determined by the lug area, while on soft soils, the total area determines the footprint [8]. The lug design is also designed for self-cleaning on very muddy terrain, which in many cases makes it impossible to effectively use traditional road tires in crops.

Soil compaction changes depending on the moisture content and the load applied by the machines [3,14]. Furthermore, straw mulch on the soil can mitigate compaction in tropical agriculture, mainly because the straw serves as a buffer or pressure attenuator between the wheels and the soil physical structure [8,15].

Controlled tests with agricultural tires allow the development of new wheel systems on machines, in addition to allowing mathematical estimation of the effect on the soils or crops [12,16,17]. These tests are mainly relevant for tropical conditions, where several harvests are carried out per year, to maintain soil conditions suitable for cultivation [18].

Applying straw to the soil helps regulate temperature, minimizes erosion risks, and improves moisture retention and nutrient availability for crops [19,20]. However, certain management practices remove plant cover or crop residues for industrial purposes, such as second-generation ethanol production. This biomass removal can diminish soil fertility and reduce the soil's ability to buffer the mechanical impacts from agricultural machinery.

This study focused on evaluating how different tire models and straw amounts in the soil can mitigate compaction. To achieve this, we used tires widely applied on cargo vehicles in tropical crops, including road tire models that equip cargo trucks. Innovatively, a comparison by different analysis methods and tire contact surfaces allowed us to determine the impact of each tire type on rigid and deformable surfaces and estimate important parameters for more efficient systems' modeling, such as total contact area, tire gripper contact area, pressure applied and critical compaction depth.

2. Materials and Methods

2.1. Site of Study and Static Tire Test Unit (STTU) Details

The studies were developed in the Department of Agricultural Engineering of the Faculty of Agronomic Sciences in São Paulo State University (Nempa/Botucatu). Static tire test unit—STTU was used for all tire–surface interaction evaluations.

In the test unit, the wheels are mounted on the central support of a metal structure, to which loads are applied to different surfaces. The loads are imposed on the surface wheelset through an electro-hydraulic system, controlled by maneuvering devices, electric motor, hydraulic pump, and piston acting on a wheelset axle (Figure 1).

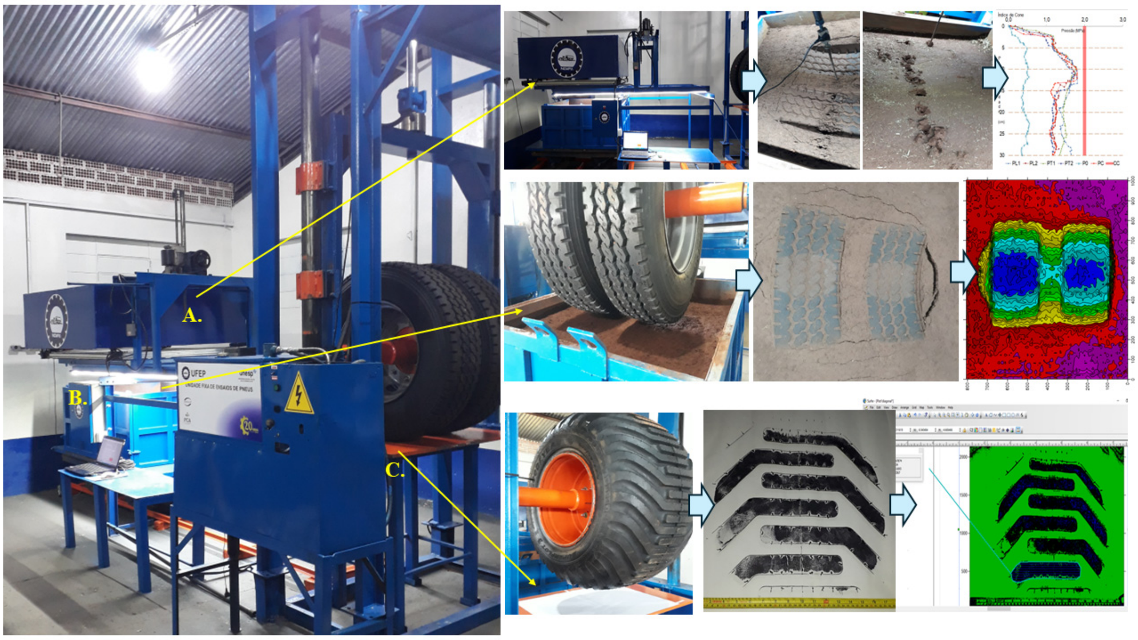

Figure 1. Static tire test unit (STTU). (**A**) Scanner system and soil penetration resistance (SPR); (**B**) soil bin (deformable surface); (**C**) steel desk (rigid surface).

Tests were carried out with three types of agricultural tires based on four contact surfaces. The tires chosen for the research are commonly mounted on cargo vehicles in sugarcane fields. The STTU was equipped with a standardized digital soil bin scanning system (soil box) and an electromechanical penetrometer (Figure 1A), as well as a deformable soil bin surface (Figure 1B) and a rigid surface (Figure 1C).

During all controlled tests, the STTU was activated at a constant tire descent speed until the force of 50.5 kN was reached in the soil bin. This load was selected because it is the recommended maximum limit for the selected tires in the manufacturer's catalog. When this load was reached, a wait of ten seconds was imposed and then the wheelset was raised to its initial position.

2.2. Rigid Surface Tire Tests

The tests on a non-deformable surface were made to describe the tire footprint on a rigid surface in controlled conditions. In these tests, white paper (cardboard) is placed on the steel desk, then the tire is painted with black printing ink and the STTU activated under standard test conditions (load of 50.5kN for 10 s).

After each load application, the tire was returned to its original position. The cardboard was then removed and replaced with a fresh sheet on the steel surface. This process was repeated three times for each tire model, resulting in a total of nine samples collected on a rigid surface.

After applying loads to the STTU, the papers were digitally scanned and loaded into the Surfer Golden software system V.16 to determine the gripper contact areas (Grip_CA), representing the tire's grip area and its design; total contact area (RS_CA), representing the total contact area of the tire on the non-deformable surface; length (RS_Length) and width (RS_Width), representing the maximum width and length dimensions of the contact area to each tire model footprint (Figure 1C).

The contact areas obtained on rigid surfaces were compared with the results on deformable surfaces to deformable surface total contact area (DS_CA), and footprint area (DS_Footprint) to describe the predicted deformation in the soil bin.

2.3. Tires' Performance Evaluation

Three tire construction models were used to test interaction with four different surfaces, one non-deformable (steel desk) and three soil surfaces with and without plant cover (straw). Tires are representative of cargo machines used in crop management in tropical agriculture, usually installed on wagons and transport vehicles: p1—road radial truck model in double fitting; p2—agricultural high flotation radial tire with improved flexibility; p3—bias-ply tire widely used in cargo machines and implements (Table 1).

Table 1. Technical characteristics and tire specification in the controlled tests.

Type	Tire	Width (mm)	Diameter (mm)	Static Radio (mm)	Cargo Index	Inflation Pressure (kPa) *
275/80R22.5 (double)	p1 	275	1029	515	149 K	717
600/50R22.5	p2 	616	1181	510	165 A8	283
600/50-22.5	p3 	600	1172	572	165 A8	283

* Tire inflation pressures were adjusted based on the recommendation of the Latin American Tire and Rim Association [21].

2.4. Soil Bin Test

The soil chosen for the research is representative of grain and energy production in the Brazilian Cerrado biome. The soil classification was a typical Hapludox for soil taxonomy [22], or Latossolo Vermelho Amarelo according to the Brazilian Soil Classification System [23].

Soil characteristics and vegetation cover (straw) adopted for the soil bin test were estimated to simulate sugarcane crop residue (Figure 2A). The straw was obtained from a commercial sugarcane field, SP80-1816 variety second ratoon (Figure 2B). To collect the straw, $1m^2$ areas were delimited using a measuring tape and rope. The edge areas were cut, and the samples were weighed on an analytical balance to assess the total coverage in Mg ha^{-1}. The straw moisture content was evaluated using the oven method; ten samples were dried at 65 °C for 48 h, resulting in an average moisture content of 50%.

Figure 2. Procedures for assembling soil bins under control conditions to simulate agricultural soil—Nempa/Botucatu laboratory. (**A**) Selection of plant material in sugarcane commercial crops (straw); (**B**) quantification of straw, biomass water content and distribution over the soil; (**C**) assembling the soil bin with controlled density and moisture; (**D**) distribution of cover over the soil in different quantities; (**E**) assessment of cover and removal of a sample of the initial soil penetration resistance from the soil bin; (**F**) application of load with the wheel on the soil bin; (**G**) removal of straw to assess soil deformation; (**H**) soil scanner (Lidar) to assess footprint; (**I**) assembling 3D maps of each soil tank; (**J**) assessment of soil penetration resistance in a soil bin transect; (**K**) unloading the soil tank; (**L**) standardization of moisture, sieving and loading the tank for a new test cycle.

Straw management in crops can be carried out in several ways, with the common practice being to collect the straw completely after harvest [24], fully remove the coverage by a soil sweeping operation (keeping the soil bare), collect the straw partially, keeping 50% of the initial quantity, and keeping the straw completely on the soil surface, covering 100%. Since sugarcane produces a different quantity of straw depending on the cultivar or variety, we chose three quantities of residue for this research.

Three soil surface straw levels were selected: 0 Mg ha^{-1} (bare soil); 15 Mg ha^{-1} (50% straw collection) and 30 Mg ha^{-1} (100% straw maintenance). These quantities represent different profiles of agricultural properties that collect all or part of the straw from the crop. These field conditions were reproduced in standard soil boxes (soil bins).

Soil bins were assembled to standardize, under controlled conditions, to the soil of the sugarcane crops at moisture levels close to the friability point. The soil was arranged in layers in the tanks (soil bins), previously homogenized to the desired water content (20 ± 1%) and the layers were compacted with the mechanical device to reach a value of 1.6 g cm^{-3}. The soil bins were constructed of steel with external reinforcement measuring 1.03 m wide, 1.30 m long, and 0.60 m high (Figure 2C).

At each soil bin assembly, the soil was sieved to break up clods and larger aggregates. The sieve used was constructed with a mesh equivalent to 3 mesh. The soil was sieved manually for each soil bin layer with 0.2 Mg of total mass. Each soil bin totaled 1 Mg of net soil mass. The average density was 1.59 ± 0.2 g cm^{-3} in all evaluations with the standard procedure. After the standardized soil tank assembly, the coverage was randomized by drawing lots, and straw was applied to the surfaces in amounts of 0, 15 and 30 Mg ha^{-1} (Figure 2D–F).

After completing the assembly of the standard soil bin, the STTU was activated under standard load conditions (50.5 kN) for 10 s. After the load was applied, the wheel was returned to the initial position and the straw was removed from the surface, using a brush, to collect the footprint deformation and compaction results (Figure 2G,H).

After the cover was removed, the soil tank was moved by rail to the STTU scanner to determine soil deformation (Figure 2I) and then for soil penetration resistance (SPR) analysis with an electromechanical penetrometer (Figure 2J). STTU digital scanning and the electromechanical penetrometer enabled the determination of total contact area (DS_CA) by the wheelset (m^2) and the SPR (MPa) in each treatment. The data were then transferred to the Golden Surfer v.18 software, where surface maps were generated.

In the soil bin, total contact area (DS_CA) represented the total area influenced by the wheelset after applying the load on the STTU. The DS_Footprint represented the total area deformed by the tire only. In addition to the total areas, measurements were also taken of depth, length, width and sinking in the soil bin.

Contact pressures were obtained by simply dividing the contact area on each surface as a function of the applied load. RS_PC (Equation (1)) indicates a rigid surface contact pressure, Grip_PC (Equation (2)) indicates the pressure applied only by the tire grippers, and DS_PC indicates the pressure on a deformable surface (Equation (3)).

$$\text{RS\_PC} = 0.001 \times (\text{Standard Load Applied}/\text{RS\_CA}) \quad (1)$$

where RS_PC (MPa) denotes rigid surface pressure contact; standard load applied (50.5 kN) indicates in STTU at standard conditions; RS_CA is rigid surface contact area, obtained in rigid surface tests. This figure, 0.001, is a constant conversion of N/m^2 to MPa.

$$\text{Grip\_PC} = 0.001 \times (\text{Standard Load Applied}/\text{Grip\_CA}) \quad (2)$$

where Grip_PC (MPa) is rigid surface pressure contact in tire grip; standard load applied (50.5 kN) indicates in STTU at standard conditions; Grip_CA is the contact area to the grip of the tires. This figure, 0.001, is a constant conversion of N/m^2 to MPa.

$$\text{DS\_PC} = 0.001 \times (\text{Standard Load Applied}/\text{DS\_CA}) \quad (3)$$

where DS_PC (MPa) is deformable surface pressure contact (bare soil); standard load applied (50.5 kN) indicates in STTU at standard conditions; DS_CA is total contact area in soil bin. This figure, 0.001, is a constant conversion of N/m^2 to MPa.

2.5. TASC Simulation Model

For the simulation of stress caused by the tires in the subsoil, the "Tyres/Tracks and Soil Compaction" (TASC) model was used [25]. According to the authors, the parameters affecting soil stress can be recorded and validated through soil physical testing methods to minimize the risk of soil compaction in agriculture and forestry.

Specific details were inserted in the TASC model for stress prediction on the ground. For each tire model, we evaluated soil type, such as grain size ratio or "texture", soil bin humidity, maximum crop depth where roots can be harmed, standard soil tank surface index, classified into three categories, "soft" and "semi-firm" and "firm").

From the obtained tire contact area on different surfaces, the tire type (tire ratio and tire width), tire constructive model ("d" for bias-ply tire and "r" for radial tire), tire size and tire inflation pressure were considered for the specific characteristics of loaded tire models in this study.

The details of each tire shown in Table 1 were input into the simulation system along with the footprint length and width information. In addition, the soil moisture content was fixed at 21% and the soil type was semi-firm on the surface with 31% clay and 5% silt.

2.6. Statistical Analysis

A completely randomized (DIC) experimental model was used for the 12 treatments (4 surfaces and 3 tires) with 3 replications. Pearson's linear correlation was analyzed for settlement area data as a function of different amounts of straw, as well as for SPR.

The contact areas on the hard surface were compared with the contact areas on the ground without vegetation cover. The evaluations of the effect of vegetation cover were compared separately for bare soil versus different amounts of straw in the cover.

Data were submitted to the Shapiro–Wilk normality test; Bartlett and Levene's homogeneity of variance; analysis of variance and, when necessary, the Tukey test at 5% probability. All applied analyses were developed in the R software statistics system, version 4.5.1.

3. Results and Discussion

3.1. Contact Area Test

The tire contact areas showed significant differences between the models and the surfaces. A significant increase in the contact areas on a deformable surface compared to a rigid surface show that the rigid surface underestimates the real tire contact area under field conditions. The smallest contact areas were obtained on the dual truck tire (p1); these small areas added together are not equivalent to the areas of the agricultural tires (Figure 3).

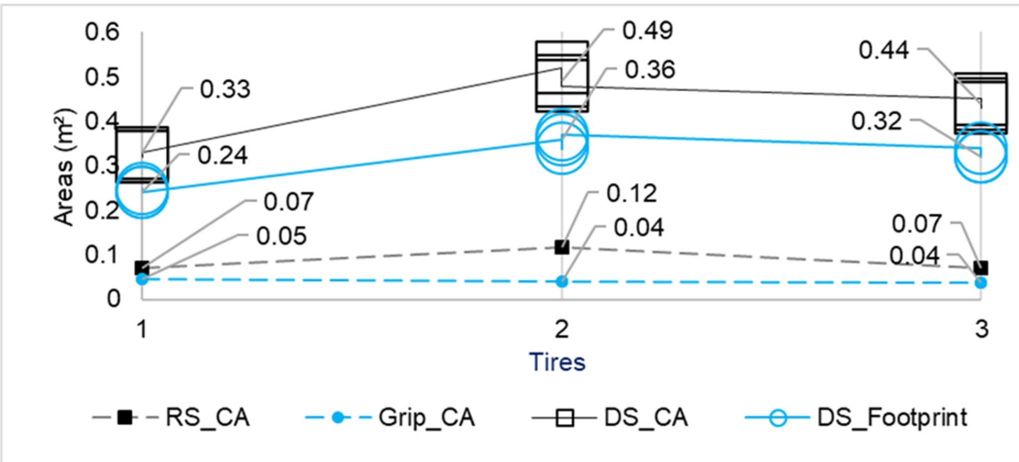

Figure 3. Total contact areas on rigid surface (RS_CA), soil bin (DS_CA), and grip (claws) area (Grip_CA) for each tire model: p1—road truck model, double fitting; p2—agricultural high flotation radial tire with improved flexibility; p3—bias-ply tire widely used in cargo machines and implements.

The road tire model (p1) exhibited a contact area of 0.33 m^2, compared to 0.49 m^2 and 0.44 m^2 for P2 and P3, respectively. On deformable surfaces, the contact area increased 4.7 times for p1 and p2, and 6.8 times for P3. Cargo tire contact areas should be estimated using different methods than traction tires [1], as this factor is crucial in determining the intensity of dynamic loads on the soil [26–28]. Consequently, the performance of a wheelset in agricultural applications is highly dependent on its contact area.

According to Thorpe et al. [29], tire contact area expands when soil moisture content is high, and soil density is lower. Conversely, more compact and dry soil reduces the tire's contact area. This trend was clearly observed in the comparison between rigid and deformable surfaces in this study.

The p1 tire is designed for traffic on hard, paved surfaces. However, in agricultural environments, where the soil is more plastic, the tire tends to sink deeper, increasing rolling resistance and fuel consumption. The grip dynamics differ between road truck tires and agricultural tires, as surface irregularities influence rolling behavior.

Road models experience less bearing vibration due to shallower clefts [30]. Additionally, the tread design (Grip_CA) can create an uneven contact area on harder surfaces, such as roads and superficially compacted soils [31].

The relationship between the total tire area and its width is crucial for implementing strategies to control machine traffic in tropical agriculture, minimizing impacts near the crop root zone. When adopting traffic control measures, selecting tires with the smallest possible width is essential. In this regard, our results highlight the advantages of using p3, the bias-ply tire, under these conditions (Figure 4).

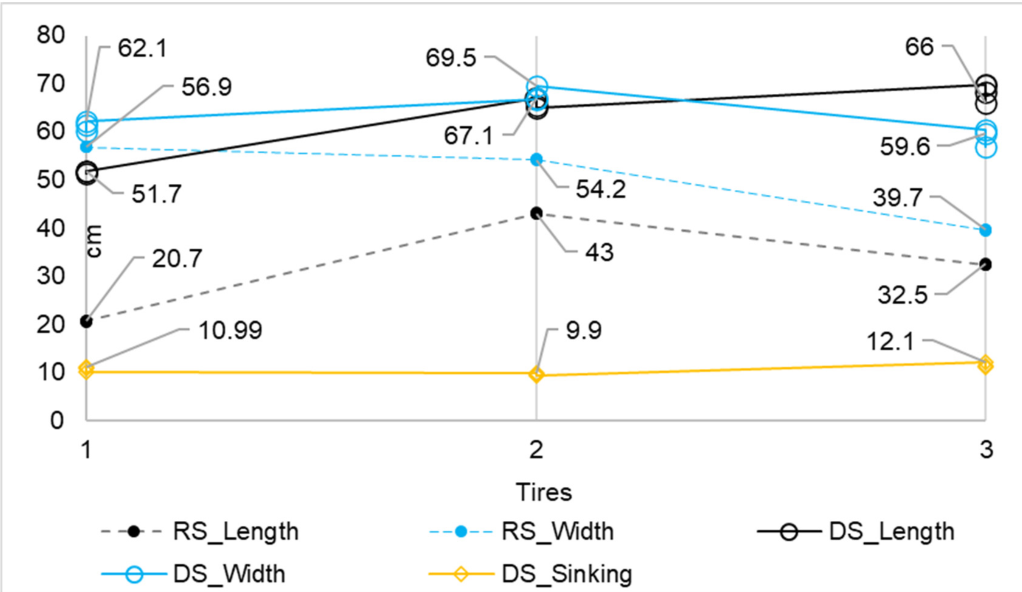

Figure 4. Sinking, width and length contact on a rigid (RS) and deformable surface (DS): p1—load truck model, double fitting; p2—agricultural high flotation radial tire with improved flexibility; p3—bias-ply tire, widely used in cargo machines and implements.

The p1 tire exhibited the highest value of total and specific areas due to the high percentage of grip in the footprint. In agricultural settings where controlled machine traffic is implemented, it is beneficial for tires to have higher inflation pressure and a narrower working width. This allows them to travel farther from planting lines, dissipating soil pressures away from agronomic crops, which helps reduce compaction [31].

Additionally, more compacted soil in traffic zones lowers fuel consumption for machinery. The authors of [32] emphasized that controlled traffic is just one aspect of soil protection; other systemic measures, such as moisture management for machine entry and careful tire selection to minimize soil impact, must also be considered.

Relationships between the footprint and the machine traction capacity are shown in [16,30]. It has been inferred that numerous factors influence tire deformation under rolling conditions. However, dynamic evaluation estimates are crucial for actively adjusting parameters based on agricultural operations. While this approach has not yet been explored for cargo tires, it presents a promising avenue for future research.

Relevant research on solo wheel interaction [2] stated that mathematical estimative modeling can predict areas prone to compaction or physical degradation in agricultural soils. The authors suggest that soil may exhibit a memory effect due to the stress imposed by machine traffic.

3.2. Pressures Appllied

Tire selection plays a crucial role in determining the soil compaction intensity, directly impacting crop productivity; the authors of [5] reported a 47% reduction in sugarcane yield due to soil physical barriers. Figure 5 illustrates the contact pressures of each tire model, with the lowest pressures observed in the radial model (p2). Conversely, the highest pressures were recorded for p1 and p3.

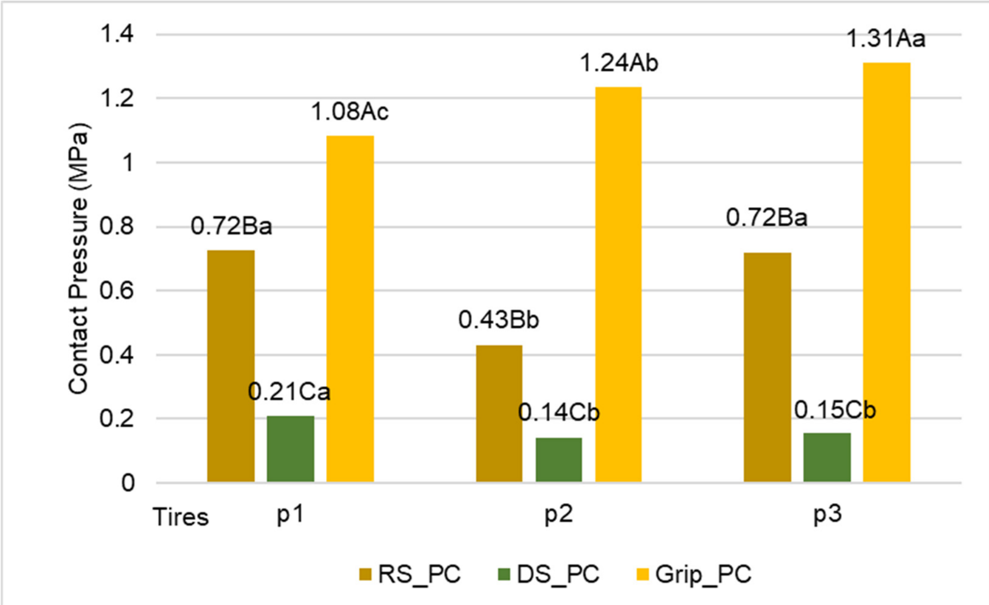

Figure 5. Contact pressures (PC) on rigid (RS) and bare soil (DS) surfaces: p1—radial truck model, double fitting; p2—agricultural high flotation radial tire with improved flexibility; p3—bias-ply tire widely used in cargo machines and implements. Tukey Test ($p < 0.05$): different capital letters indicate contact pressure differences between RS, Grip_PC and DS for each tire model; different lowercase letters indicate differences between tires for each PC.

However, the radial truck tire, when mounted in a double set, exhibited statistically similar results to the bias-ply tire, suggesting that road tire models show similar conditions to agricultural tires.

The highest pressures are applied by grips, with a significant difference in the RS and DS. The highest contact pressure in the grips was for p3; this is due to the smaller contact grips number in this tire model, followed by the radial model. These tires have a large total contact area, but the proportionality of grip areas is low (Figure 5).

The tire design is crucial for the pressure applied on firm ground. However, tire designs with many grip areas can affect self-cleaning when working on clay soils, so this should be taken into consideration when selecting tires.

Static tire tests play a crucial role in enhancing simulation systems, improving tire models, and refining their interaction with running surfaces [33]. Our findings contribute to computational and simulation models that analyze wheelset dynamics on the ground, as demonstrated by [16,17].

The pressure exerted on the soil is directly influenced by the tire's contact area. In field conditions, lower internal tire pressures are often used to increase the contact area and reduce soil pressure. However, excessive pressure reduction can weaken the tire's internal structure and shorten its lifespan.

From a market perspective, road tire models offer competitive pricing and a wide range of options, but their higher contact pressures can significantly impact soil conditions. When mechanized operations extend beyond the soil friability zone, agricultural tire models—with a larger total contact area and lower internal inflation pressures—are the preferred choice for minimizing soil compaction.

Soil moisture significantly influences soil stress, as the soil solution acts as a lubricating agent between particles, facilitating the reconsolidation process. According to [34], deep soil deformation can be estimated through controlled testing and the determination of rolling radius wheels.

Tire deformation on soil directly impacts traction capacity and rolling resistance [16]. Greater deformation leads to increased sinking and higher energy demands. Additionally, the intensity of machine impact is influenced by the amount of straw present on the soil surface.

3.3. Straw Effect on Contact Area and Soil Penetration Resistance

The radial tire (p2) shows the largest contact areas, followed by bias-ply model (p3) and road truck model (p1). Therefore, the highest pressures were applied by the road model to the soil (Figure 6).

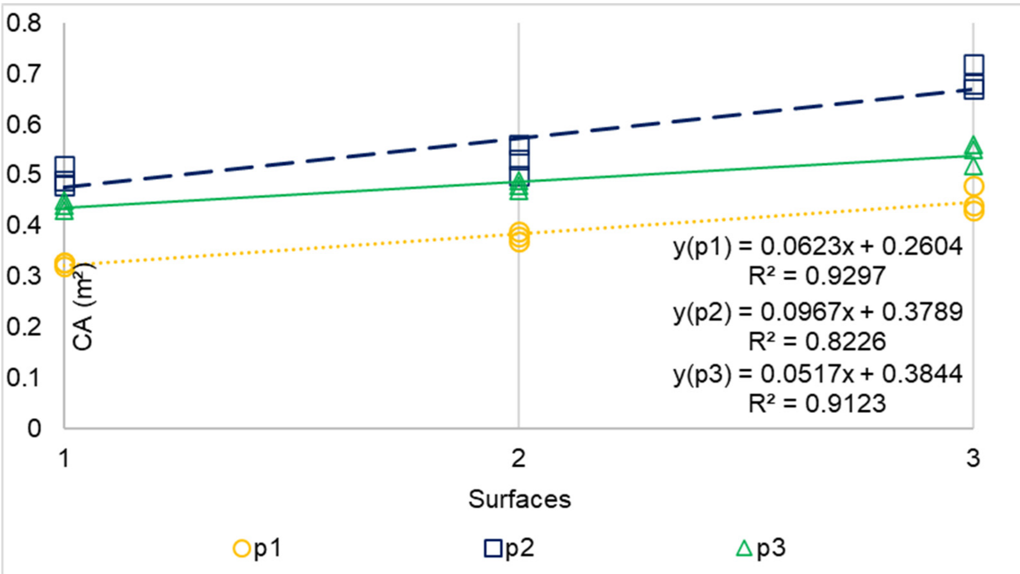

Figure 6. Tire contact area (CA) on different soil bin surfaces (bare soil, 15 and 30 Mg ha^{-1} straw); p1—road truck model, double fitting; p2—agricultural high flotation radial tire with improved flexibility; p3—bias-ply tire widely used in cargo machines and implements.

Larger contact areas enable lower pressures to be applied to the soil. In this study, agricultural tires and straw maintenance were identified as key factors in reducing soil stress. Sugarcane production units that maintain full straw coverage can mitigate the impact of road tires by using double assembly configurations. For mills that partially collect straw or cultivate low-biomass varieties, these benefits persist, albeit to a lesser extent.

The larger tire contact areas with the soil allow lower contact pressures to be applied, thus causing less stress in the root growth zone of crops. Our results showed the lowest SPR to agricultural tires and the highest resistance for road tires (Figure 7). The use of road tires on uncovered soil can irreversibly damage the soil structure.

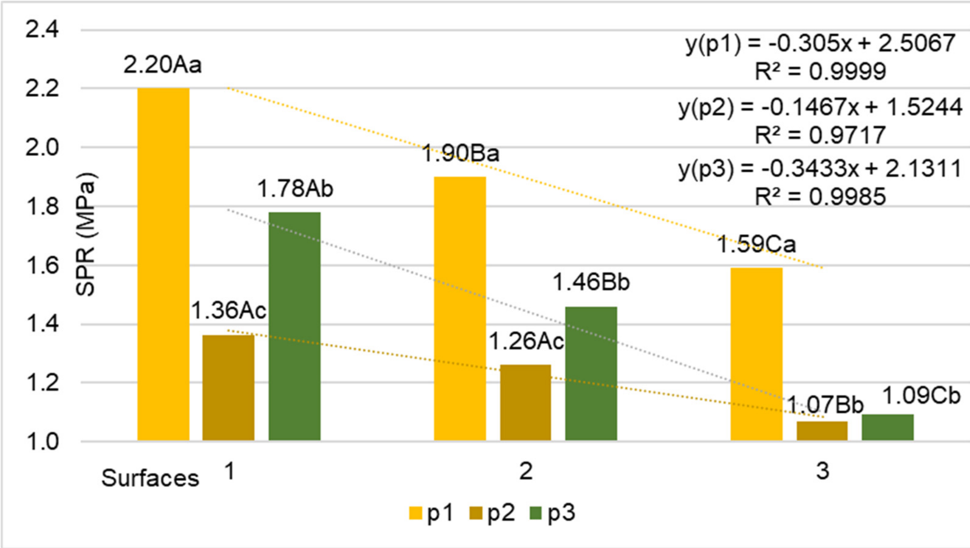

Figure 7. Soil penetration resistance (SPR) in each surface for three tire models. p1—road truck model, double fitting; p2—agricultural high flotation radial tire with improved flexibility; p3—bias-ply tire widely used in cargo machines and implements. Tukey Test ($p < 0.05$): different capital letters indicate differences between tires in three surfaces; different lowercase letters indicate differences between tires in the same surface.

On bare soil, the soil resistance reached 2.6 MPa in the surface layer, with an average of 2.2 MPa, making it difficult for the sugarcane roots to grow [4]. The positive effect of vegetation cover is increasing the contact area of the tires and reducing soil stress. Our results concur with [28], where the analytical method overestimates the contact area, while digital analysis provides more accurate measurements.

Straw reduces the soil's resistance to penetration and better disperses compaction energy. We found that if a minimum of 15 Mg ha^{-1} of vegetation cover is maintained on the soil, penetration resistance is severely reduced and contact areas are enlarged. According to [3], soil compaction is the main factor limiting growth and crop development, as it limits root growth and reduces the plant's absorption of nutrients and water.

The data linearity (r^2—0.99; 0.97; 0.99) shows that the straw cushions the pressures on the ground, increases the contact area and reduces the tire pressures applied. The negative angular coefficient (Figure 7) indicates its SPR decreases as the straw increases, like the contact area (Figure 6), which increased as soil cover was increased.

The sugarcane production units have recently adopted the collection of straw for use in the mill, in the production of second-generation ethanol or in direct burning boilers. However, collecting the material, in addition to being expensive, can cause soil stress.

Computer simulation models, such as those evaluated by [6,17], need more information about the contact areas, footprint and soil deformations to become more assertive, thus our research opens new frontiers of knowledge.

New alternatives for wheelsets and tire models [35] at a lower cost can be applied in sugarcane production if the soil moisture and the amount of covering plant material are respected. We emphasize that our results are strictly applicable to the type of soil and tires that we investigated in the research, but further extrapolations require studies with other soil conditions.

3.4. Soil Stress Simulation

The distribution of loads in the subsoil becomes relevant for planning traffic machines depending on the type of wheel, moisture conditions, and soil texture. Soil stress simulations, conducted in static tests like those in this study, may underestimate the propagation in the soil by more than five times [36].

Due to the turbulence of contact between the machine and the soil under static conditions, loads are unevenly distributed in the soil. In the static simulation, the maximum stress was applied by tire p1 (Figure 8), a dual-mounted road truck wheel at 0.27 MPa. If extrapolated to dynamic conditions, this could reach values between 1.35 and 1.89 MPa, five to seven times higher than the static condition.

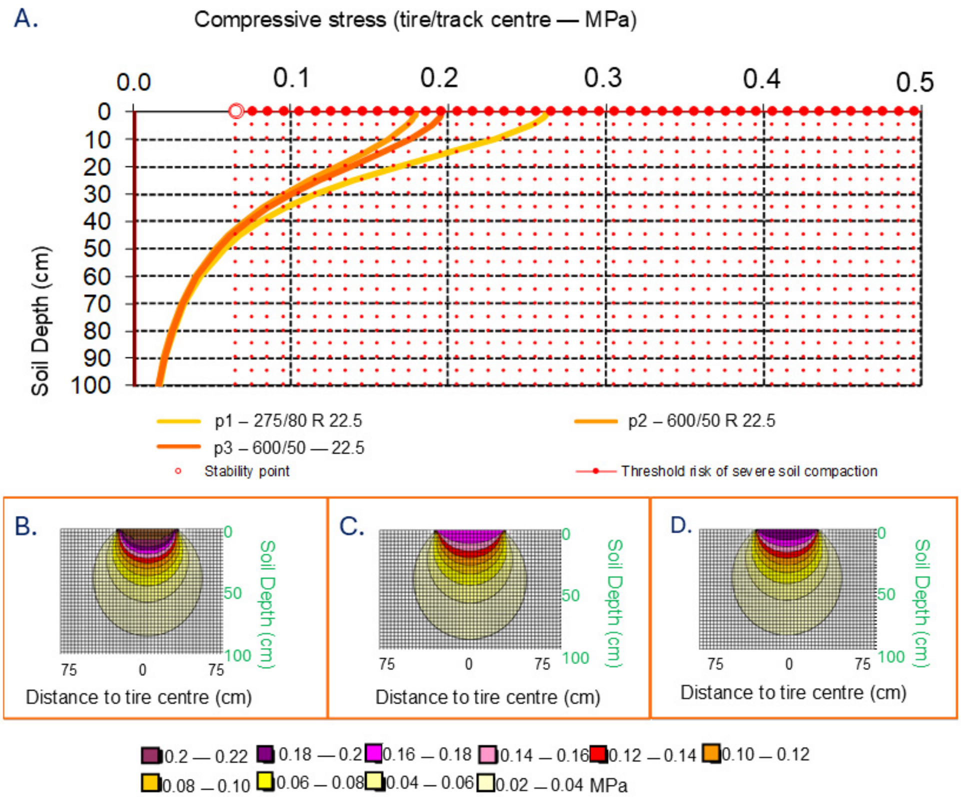

Figure 8. Soil stress distribution with no-straw—bare soil (0 Mg ha^{-1}) using different tire models; p1: road truck model, double fitting; p2: agricultural high-flotation radial tire with improved flexibility; p3: bias-ply tire widely used in cargo machines and implements. (**A**) Compressive stress curves as a function of depth for each tire model; (**B**) deep load bulbs applied by tire p1 (275/80 R 22.5); (**C**) deep load bulbs applied by tire p2 (600/50 R 22.5); (**D**) deep load bulbs applied by tire p3 (600/50 — 22.5).

The high surface stress caused by the tires would make truck wheels unsuitable for use in agricultural fields [37]. However, the studies conducted in this research require further confirmation through stress sensors installed directly in the soil and validation of soil pre-consolidation pressure.

Comparing the load bulbs of tires on bare soil, the risk of soil compaction is severe: up to 46 cm depth with the truck tire (p1), followed by 43 cm with the bias-ply tire (p3) and 42 cm with the radial tire (p2). At a depth of 10 cm, where a significant portion of the plant root system develops, p1 showed a stress of 0.24 MPa, followed by 0.18 MPa and 0.17 MPa for p3 and p2, respectively (Figure 8B–D).

The results aligned with those obtained by [5], where the highest pressures applied to the soil in a sugarcane field were from truck tire loads. However, the authors also found that other cargo vehicles increased soil compaction beyond acceptable levels. On bare soil, excessive straw removal compromises the soil's physical quality, as it becomes exposed to load applications from wheels. Additionally, the lack of cover reduces carbon stocks and negatively affects root growth and sugarcane productivity [4].

In a pioneering study evaluating the distribution of compressive stress in the soil resulting from loads applied by tracks, the estimated internal stress values were up to four times higher under dynamic conditions than those observed in static tests [38].

The soil load application negatively impacts any type of agricultural system, even with low-intensity loads, as soil penetration resistance can exceed acceptable limits [39]. In the static simulation of our study, even in covered soil, the maximum stress was applied by tire p1 (Figure 9) at 0.20 MPa. If extrapolated to dynamic conditions, this could reach values between 1.0 and 1.4 MPa, five to seven times higher than the static condition. All tire models showed significant impact on soil structure.

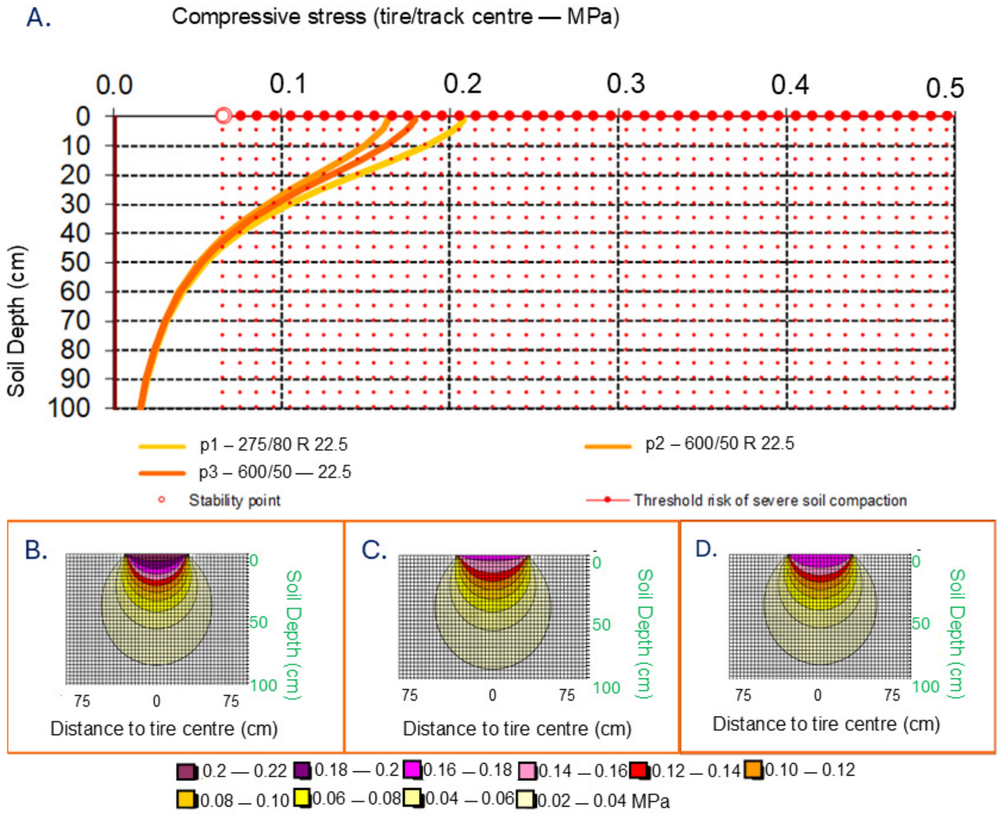

Figure 9. Soil-stress distribution with straw (15 Mg ha^{-1}) using different tire models; p1: road truck model, double fitting; p2: agricultural high-flotation radial tire with improved flexibility; p3: bias-ply tire widely used in cargo machines and implements. (**A**) Compressive stress curves as a function of depth for each tire model; (**B**) deep load bulbs applied by tire p1 (275/80 R 22.5); (**C**) deep load bulbs applied by tire p2 (600/50 R 22.5); (**D**) deep load bulbs applied by tire p3 (600/50—22.5).

Our results align with [14], who found soil compaction in various configurations of cargo vehicles in sugarcane fields affecting even deeper layers. The increase in soil density reported by the authors was up to 7%, with a severe reduction in soil macroporosity.

A reduction in soil stress is observed due to the presence of vegetative cover for all tire types. This was confirmed by [28], where straw proved beneficial in mitigating the negative effects of agricultural mechanization on soil structure.

At a depth of 10 cm, compared to bare soil, p1 showed an average reduction of 25% in subsoil stress (0.18 MPa). This reduction was 17.6% in p2 (0.14 MPa) and 11.1% in p3 (0.16 MPa), respectively (Figure 9B–D). Summing the percentage reductions in stresses, our findings suggest that 15 Mg ha^{-1} of straw on the soil provides a total buffering capacity of 18% in attenuating total stresses in the surface soil layers (up to 10 cm).

The simulation indicated a severe risk of compaction down to 44 cm depth with the truck tire (p1), followed by 42 cm with the bias-ply tire (p3) and 41 cm with the radial tire (p2). According to [15], sugarcane fields that maintain larger amounts of straw (>10 Mg ha^{-1}) increase the apparent soil support capacity by up to 7%, though this effect is not entirely sufficient to mitigate compaction from high loads applied by agricultural machinery.

Trucks pose a greater risk of soil compaction [14], reaching depths of up to 0.35 m. The tractor and wagon trailer had a lower impact, with compaction detected up to 0.29 m depth. Straw reduces the rate of density change in loose soils under low pressure, but in high-pressure situations (>0.4 MPa), it can increase compaction in these soils. For already compacted soils, larger amounts of straw reduce the compaction rate [15].

The progressive straw increase on the soil surface can mitigate compaction and stress distribution in the soil for all tire models, even when added to soil already covered with vegetation (Figure 10). Additionally, as an extra benefit, straw on the soil helps reduce erosion, and its fibrous structure and high biomass content make it particularly effective in moisture retention and protection against mechanical impacts, promoting a better quality of plant raw material [40].

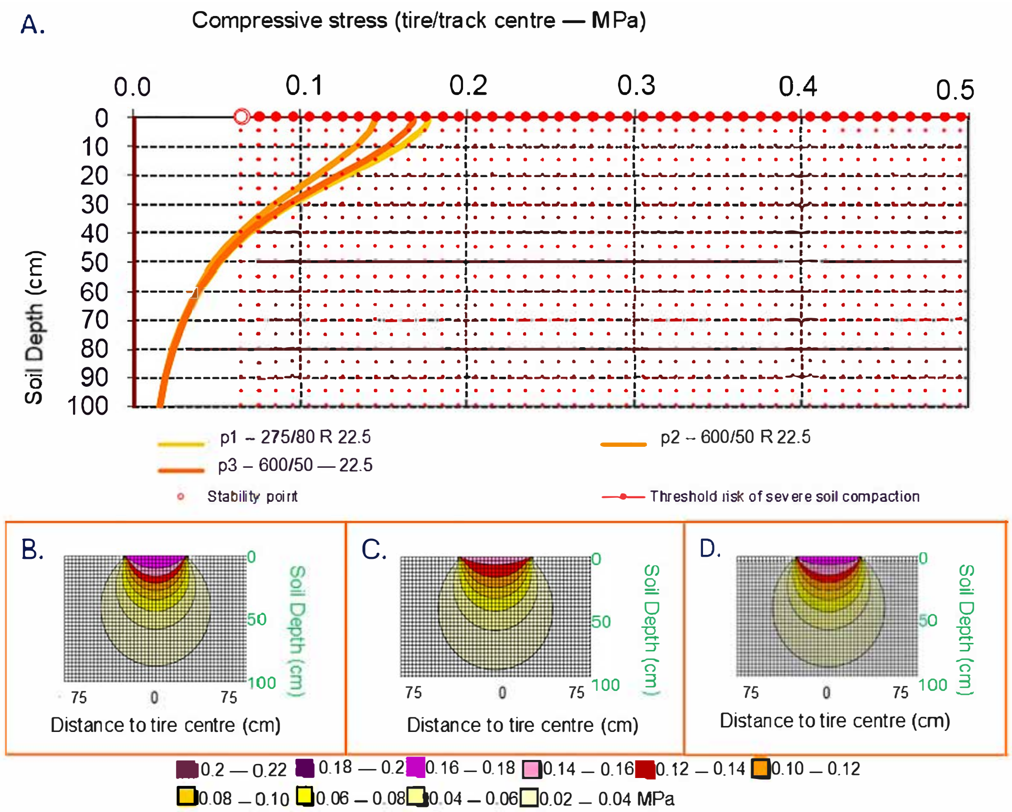

Figure 10. Soil stress distribution with straw (30 Mg ha^{-1}) using different tire models; p1: road truck model, double fitting; p2: agricultural high-flotation radial tire with improved flexibility; p3: bias-ply tire widely used in cargo machines and implements. (**A**) Compressive stress curves as a function of depth for each tire model; (**B**) deep load bulbs applied by tire p1 (275/80 R 22.5); (**C**) deep load bulbs applied by tire p2 (600/50 R 22.5); (**D**) deep load bulbs applied by tire p3 (600/50—22.5).

The simulation indicated a severe risk of compaction down to 42 cm depth with the truck tire (p1), followed by 39 cm with the bias-ply tire (p3) and 41 cm with the radial tire (p2). In addition to acting as a cushion, sugarcane straw is an essential carbon source, contributing to improved soil structural stability and biological activity, which can reduce compaction risks and enhance plant growth.

At a depth of 10 cm, compared to the 15 Mg ha^{-1} cover, p1 showed an average reduction of 11.1% in subsoil stresses (0.16 MPa). This reduction was 7.1% in p2 (0.13 MPa) and 6.2% in p3 (0.15 MPa) (Figure 10B–D). Summing the percentage reductions in stress, our findings suggest that an additional 15 Mg ha^{-1} of straw on the soil (total 30 Mg ha^{-1}) provides an overall buffering capacity of 8.1% in mitigating soil stress (up to 10 cm depth).

Our results align with [15], where the presence of sugarcane straw influences the propagation of stress in the subsoil, reducing compaction under low pressure (<100 kPa). However, it is not sufficient to eliminate the risks of compaction in highly mechanized areas or those subjected to heavy loads.

Sugarcane straw, unlike numerous other agricultural residues, exhibits considerable potential for bioenergy conversion. It serves as a valuable feedstock in the production of second-generation ethanol and the generation of bioelectricity within industrial processing facilities. Consequently, it is imperative to adopt management strategies and a holistic approach when determining the optimal allocation of this biomass between soil retention and industrial utilization.

Innovative approaches to machinery management, such as controlled traffic farming (CTF), have emerged as viable strategies for soil conservation and the mitigation of environmental impacts [41]. Moreover, cover crops like Brachiária contribute to soil protection by buffering against the mechanical stress of agricultural equipment and safeguarding against adverse climatic conditions.

It is important to emphasize that our results are strictly applicable to the soil type we investigated in this study. These soils are representative of Brazilian agriculture, but further investigations need to be conducted in other soil conditions to fully validate the model. In agreement with our results, other studies found that wider tires apply lower loads on the soil [42]. Wider tires reduce soil compaction compared to narrower tires, especially up to a depth of 20 cm. Thus, our study reinforces that the proper selection of tires can minimize compaction and preserve soil integrity, contributing to more sustainable agriculture.

Recent studies show that it is possible to adapt road wheelset and tire technologies to field conditions through mathematical modeling [43]. Our findings contribute to a better understanding of these relationships under real-world conditions.

4. Conclusions

This research evaluated the interaction of different models of cargo tires applied in agriculture and their relationships on different surfaces. The tire model and the surface characteristics significantly affect the tire contact area, pressure on the soil, and compaction risk. The main findings can be highlighted as follows:

(1) The rigid surface yielded the smallest contact areas, which resulted in increased wheel pressure.
(2) The deformable surface increases the contact area by at least 4.7 times compared to the rigid surface, regardless of the tire.
(3) On the deformable surface without vegetation cover (bare soil), the highest subsoil stresses were observed. Straw on the soil increases the tire's contact area and reduces compaction.
(4) All tire models had a significant impact on the topsoil, leading to the risk of compaction. However, the greatest pressure was imposed by the road truck tire (p1). On the other hand, the radial tire (p2) caused the lowest stress levels.
(5) The addition of 15 Mg ha^{-1} of straw to bare soil improved the SPR by 18%. The increase from 15 to 30 Mg ha^{-1} improved SPR by 8%, indicating that there are limiting values for the effects of straw on soil protection.

Author Contributions: Conceptualization, A.C.M.F. and K.P.L.; methodology, A.C.M.F., M.B.M., S.D.S.d.M. and W.d.S.G.J.; investigation, A.C.M.F., L.S.S., M.B.M., S.D.S.d.M. and W.d.S.G.J.; data

curation, A.C.M.F., S.D.S.d.M. and L.S.S.; writing—original draft preparation, A.C.M.F., W.d.S.G.J. and L.S.S.; writing—review and editing A.C.M.F. and L.S.S.; supervision, K.P.L. and S.D.S.d.M. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brazil (CAPES)—Financial Code 001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed at the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Schjønning, P.; Stettler, M.; Keller, T.; Lassen, P.; Lamandé, M. Predicted tyre–soil interface area and vertical stress distribution based on loading characteristics. *Soil Tillage Res.* **2015**, *152*, 52–66. [CrossRef]
2. Alaoui, A.; Diserens, E. Mapping soil compaction—A review. *Curr. Opin. Environ. Sci. Health* **2018**, *5*, 60–66. [CrossRef]
3. Keller, T.; Sandin, M.; Colombi, T.; Horn, R.; Or, D. Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil Tillage Res.* **2019**, *194*, 104293. [CrossRef]
4. Barbosa, L.C.; Tenelli, S.; Magalhães, P.S.; Bordonal, R.O.; Cherubin, M.R.; de Lima, R.P.; Carvalho, J.L.N. Linking soil physical quality to shoot and root biomass production in scenarios of sugarcane straw removal. *Eur. J. Agron.* **2024**, *152*, 127029. [CrossRef]
5. Delmond, J.G.; Junnyor, W.D.S.G.; de Brito, M.F.; Rossoni, D.F.; Araujo-Junior, C.F.; da Costa Severiano, E.; Severiano, E.C. Which operation in mechanized sugarcane harvesting is most responsible for soil compaction? *Geoderma* **2024**, *448*, 116979. [CrossRef]
6. Acquah, K.; Chen, Y. Discrete element modelling of soil pressure under varying number of tire passes. *J. Terramechanics* **2023**, *107*, 23–33. [CrossRef]
7. Zhang, F.; Qiu, Y.; Teng, S.; Cui, X.; Wang, X.; Sun, H.; Fu, S. Design and Test of Tread-Pattern Structure of Biomimetic Goat-Sole Tires. *Biomimetics* **2022**, *7*, 236. [CrossRef]
8. Marques Filho, A.C.; de Medeiros, S.D.S.; Martins, M.B.; dos Santos Moura, M.; Lanças, K.P. Can the Straw Remaining on the Ground Reduce the Wheelsets Impact on Sugarcane Crop? *Sugar Tech* **2022**, *24*, 1814–1820. [CrossRef]
9. Diserens, E.; Chanet, M.; Marionneau, A. Machine Weight and Soil Compaction: TASC V2.0. xls-a Practical Tool for Decision-making in Farming 2010. Available online: https://www.tasc-application.ch/wp-content/themes/Divi-Child/downloads/6-REF239.pdf (accessed on 26 March 2025).
10. Fujita, K.; Saito, T.; Kaneko, M. Dynamic Characteristics of Rolling Agricultural Tire. *Eng. Agric. Environ. Food* **2021**, *14*, 1–12. [CrossRef]
11. Farhadi, P.; Golmohammadi, A.; Malvajerdi, A.S.; Shahgholi, G. Finite element modeling of the interaction of a treaded tire with clay-loam soil. *Comput. Electron. Agric.* **2019**, *162*, 793–806. [CrossRef]
12. Teimourlou, R.F.; Taghavifar, H. Determination of the super-elliptic shape of tire-soil contact area using image processing method. *Cercet. Agron. Mold.* **2015**, *48*, 5–14. Available online: https://repository.iuls.ro/xmlui/handle/20.500.12811/1519 (accessed on 1 April 2025). [CrossRef]
13. Yue, L.; Wang, Y.; Wang, L.; Yao, S.; Cong, C.; Ren, L.; Zhang, B. Impacts of soil compaction and historical soybean variety growth on soil macropore structure. *Soil Tillage Res.* **2021**, *214*, 105166. [CrossRef]
14. Esteban, D.A.A.; de Souza, Z.M.; Tormena, C.A.; dos Santos Gomes, M.G.; Parra, J.A.S.; Júnnyor, W.D.S.G.; de Moraes, M.T. Risk assessment of soil compaction due to machinery traffic used in infield transportation of sugarcane during mechanized harvesting. *Soil Tillage Res.* **2024**, *244*, 106206. [CrossRef]
15. Cherubin, M.R.; Franchi, M.R.A.; de Lima, R.P.; de Moraes, M.T.; da Luz, F.B. Sugarcane straw effects on soil compaction susceptibility. *Soil Tillage Res.* **2021**, *212*, 105066. [CrossRef]
16. Cutini, M.; Costa, C.; Brambilla, M.; Bisaglia, C. Relationship between the 3D footprint of an agricultural tire and drawbar pull using an artificial neural network. *Appl. Eng. Agric.* **2022**, *38*, 293–301. [CrossRef]
17. Yadav, R.; Raheman, H. Development of an artificial neural network model with graphical user interface for predicting contact area of bias-ply tractor tyres on firm Surface. *J. Terramechanics* **2023**, *107*, 1–11. [CrossRef]
18. de Oliveira Bordonal, R.; Tenelli, S.; da Silva Oliveira, D.M.; Chagas, M.F.; Cherubin, M.R.; Weiler, D.A.; Carvalho, J.L.N. Carbon savings from sugarcane straw-derived bioenergy: Insights from a life cycle perspective including soil carbon changes. *Sci. Total Environ.* **2024**, *947*, 174670. [CrossRef]
19. Gamage, A.; Gangahagedara, R.; Gamage, J.; Jayasinghe, N.; Kodikara, N.; Suraweera, P.; Merah, O. Role of organic farming for achieving sustainability in agriculture. *Farming Syst.* **2023**, *1*, 100005. [CrossRef]

20. Cheng, J.; Yang, C.Z.; Zhang, L.; Lin, Z.J.; Dang, Y.P.; Zhao, X.; Zhang, H.L. The competitive effects of crop straw return and nitrogen fertilization on soil acidification. *Agric. Ecosyst. Environ.* **2025**, *388*, 109638. [CrossRef]
21. Alapa. Associação Latino-Americana dos Fabricantes de Pneus, Aros e Rodas. Man. De Segurança Agrícola E Off Road 2019. Available online: https://alapa.org.br/manuais-e-publicacoes/ (accessed on 1 November 2024).
22. USDA Soil Survey Staff. *Keys to Soil Taxonomy*, 12th ed.; United States Department of Agriculture: Washington, DC, USA, 2004.
23. Santos, H.G.; Jacomine, P.K.T.; dos Anjos, L.H.; Oliveira, V.A.; Lumbreras, J.F.; Coelho, M.R.; Almeida, J.A.; Cunha, J.F.; Oliveira, J.B. *Sistema Brasileiro de Classificação de Solos*, 5th ed.; EMBRAPA: Brasília, DF, Brazil, 2018.
24. Leal, M.R.L.; Galdos, M.V.; Scarpare, F.V.; Seabra, J.E.; Walter, A.; Oliveira, C.O. Sugarcane straw availability, quality, recovery and energy use: A literature review. *Biomass Bioenergy* **2013**, *53*, 11–19. [CrossRef]
25. Diserens, E.; Battiato, A.; Sartori, L. Soil compaction, soil shearing and fuel consumption, TASC V3.0–a practical tool for decision-making in farming. In Proceedings of the International Conference of Agricultural Engineering, Zürich, Switzerland, 6–10 July 2014.
26. Kučera, M.; Helexa, M.; Čedík, J. Link between static radial tire stiffness and the size of its contact surface and contact pressure. *Agron. Res.* **2016**, *14*, 1361–1371.
27. Pytka, J.; Śliczniak, T.; Kasprzak, P.; Gnapowski, E. Tyre-Soil Interface Determination by Photogrammetric Method. In: IOP Conference Series: Materials Science and Engineering. *IOP Publ.* **2018**, *421*, 022–030.
28. Silva, R.B.D.; Iori, P.; Souza, Z.M.D.; Pereira, D.D.M.G.; Vischi Filho, O.J.; Silva, F.A.D.M. Pressões de contato e o impacto de conjuntos motomecanizados em Latossolo com presença e ausência de palhada de cana-de-açúcar. *Ciência Agrotecnologia* **2016**, *40*, 265–278. [CrossRef]
29. Thorpe, D.D.F.; Rolim, M.M.; Pedrosa, E.M.R.; Simões, D.E.; Cavalcanti, R.Q.; Lima, R.P.D. Impacts of bulk density and water content on the tire-soil contact area of agricultural field vehicles. *Acta Sci. Agron.* **2024**, *46*, e67906. [CrossRef]
30. Pegram, M.S.; Botha, T.R.; Els, P.S. Full-field and point strain measurement via the inner surface of a rolling large lug tyre. *J. Terramechanics* **2021**, *96*, 11–22. [CrossRef]
31. Nagaoka, A.K.; Marques Filho, A.C.; Lanças, K.P. Agricultural Tire Test: Straw Cover Effect on Reducing Soil Compaction by Cargo Vehicles. *AgriEngineering* **2024**, *6*, 3. [CrossRef]
32. Tamirat, T.W.; Pedersen, S.M.; Farquharson, R.J.; de Bruin, S.; Forristal, P.D.; Sørensen, C.G.; Nuyttens, D.; Pedersen, H.H.; Thomsen, M.N. Controlled traffic farming and field traffic management: Perceptions of farmers groups from Northern and Western European countries. *Soil Tillage Res.* **2022**, *217*, 105288. [CrossRef]
33. Becker, C.; Els, S. Effect of surface roughness on tyre characteristics. *J. Terramechanics* **2022**, *102*, 27–48. [CrossRef]
34. Karelina, M.; Balabina, T.; Mamaev, A. Wheel Rolling on a Deformable Support Surface. In Proceedings of the 2022 International Conference on Engineering Management of Communication and Technology (EMCTECH), Vienna, Austria, 20–22 October 2022; Volume 1, pp. 1–4. [CrossRef]
35. Deng, Y.; Wang, Z.; Shen, H.; Gong, J.; Xiao, Z. A comprehensive review on non-pneumatic tyre research. *Mater. Des.* **2023**, *1*, 111742. [CrossRef]
36. Araujo-Junior, C.F.; Dias Junior, M.S.; Leite, F.P.; Gaudereto, G.S. *Determination of Applied Pressure on the Soil by Forest Machines Using a Simple Equipment for Measurements. Física de Suelos Clave Para el Manejo Sostenible de los Recursos Agua y Suelos*; X Escuela Latinoamericana de Física de Suelos: Lavras, Brasil, 2009.
37. Júnnyor, W.D.S.G.; Diserens, E.; De Maria, I.C.; Araujo-Junior, C.F.; Farhate, C.V.V.; de Souza, Z.M. Prediction of soil stresses and compaction due to agricultural machines in sugarcane cultivation systems with and without crop rotation. *Sci. Total Environ.* **2019**, *681*, 424–434. [CrossRef]
38. Soane, B.D.; Blackwell, P.S.; Dickson, J.W.; Painter, D.J. Compaction by agricultural vehicles. A review. II—Compaction under tyres and other running gear. *Soil Tillage Res.* **1981**, *1*, 373–400. [CrossRef]
39. Marques Filho, A.C.; Martins, M.B.; Santana, L.S.; Lopes, A.G.C.; Sobrinho, R.L.; Souza, E.F.; Alaraidh, I.A. Effect of Soil Compaction Caused by Manual and Mechanized Harvesting Management on Sugarcane Yield. *Sugar Tech* **2025**, *27*, 1351–1361. [CrossRef]
40. Martins, M.B.; Filho, A.C.M.; Santana, L.S.; Júnnyor, W.D.S.G.; Bortolheiro, F.P.D.A.P.; Vendruscolo, E.P.; da Silva, K.G.P. Productivity and quality sugarcane broth at different soil management. *Agronomy* **2023**, *13*, 170. [CrossRef]
41. Martins, M.B.; Marques Filho, A.C.; Seron, C.D.C.; Guimarães Júnnyor, W.D.S.; Vendruscolo, E.P.; Bortolheiro, F.P.D.A.P.; Santana, L.S. Controlled Traffic Farm: Fuel Demand and Carbon Emissions in Soybean Sowing. *AgriEngineering* **2024**, *6*, 1794–1806. [CrossRef]
42. Kukharets, S.; Zabrodskyi, A.; Sheludchenko, B.; Jasinskas, A.; Domeika, R.; Šarauskis, E. Assessment of changes in soil contact stress depending on tractor tire parameters. *Sci. Rep.* **2025**, *15*, 172. [CrossRef]
43. Vieira, D.; Orjuela, R.; Spisser, M.; Basset, M. An adapted Burckhardt tire model for off-road vehicle applications. *J. Terramechanics* **2022**, *104*, 15–24. [CrossRef]