



Article

Controlled Traffic Farm: Fuel Demand and Carbon Emissions in Soybean Sowing

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Abstract: Soil compaction between crop rows can increase a machine's performance by reducing rolling resistance and fuel demand. Controlled Traffic Farm (CTF) stands out among modern techniques for increasing agricultural sustainability because the machines continuously travel along the same path in the field, reducing plant crush and compacting the soil in the traffic line. This study evaluated fuel consumption and CO₂ emissions at different CTF intensities in different soil management strategies for soybean crop. The experimental design involved randomized blocks in a split-plot scheme with four replications. The plots constituted the three types of soil management: conventional tillage, no-tillage with straw millet cover, and no-tillage with brachiária straw cover. The subplots constituted for agricultural tractors were passed over in traffic lines (2, 4, and 8 times). We evaluated agricultural tractor fuel consumption, CO₂ emissions, and soybean productivity. The straw cover and tractor-pass significantly affected the fuel consumption and greenhouse gas emissions of the soybean cultivation. Fuel consumption and CO₂ emissions were reduced due to the machine-pass increase, regardless of soil management. Thus, a CTF reduces rolling resistance and increases crop environmental efficiency. Bare-soil areas increased by 20.8% and 27.9% with respect to fuel consumption, compared to straw-cover systems. Brachiária straw and millet reduce CO₂ emissions per hectare by 20% and 28% compared to bare soil. Lower traffic intensities (two passes) showed (13.72%) higher soybean yields (of 4.04 Mg ha⁻¹). Investigating these effects in other types of soil and mechanized operations then becomes essential.

Keywords: *Glycine max*; no-till; soil compaction; sustainability; precision agriculture; soil function



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1. Introduction

Brazilian agriculture plays a prominent role in global food security, with an expected increase in its contribution to the meeting of global demands in the coming decades [1]. Soybean cultivation (*Glycine max*) represents an essential crop for Brazilian and world agribusiness because it is an important source of oil and protein for human and animal nutrition [2,3]. Recent findings have demonstrated physical conditions of high soil compaction in soybean crop development in tropical soil [4].

Soil compaction is a global environmental problem [5]. High soil density can significantly reduce crop productivity [6,7] and alter water dynamics [8]. One consequence of

compaction is a reduction in plant root growth, caused by increased mechanical resistance and a decrease in soil aeration, which reduces crop yields [9]. Compaction is typically attributed to the indiscriminate use of heavy agricultural machinery in soil with high water content [10–12]. The heavy machine traffic in no-till planting areas causes superficial compaction, mainly when the soil contains high levels of moisture. This problem is the leading cause of increased energy demand in seeding operations [13].

Currently, climate projections indicate a future increase in the frequency and severity of drought [14]. With this scenario, soil compaction's harmful effects on cultivation systems can be intensified in crops. Therefore, it is important to seek alternatives to minimize crop yield losses [15]. Not only do weather and soil conditions cause plastic soil deformation, but the accumulated traffic, as determined by the load on machinery axles, wheel number, and load distribution, can increase the negative effects on soil layers alongside cultivated areas [16].

No-tillage and minimal-tillage soil conservation management systems contribute to soil protection [17,18]. Furthermore, vegetation cover (straw) can mitigate the effects of the wheels on crops [19]. Additionally, confining machines to permanent traffic lanes restricts compaction effects and tends to limit compaction to the carriageways, allowing more significant root development in areas without traffic [20].

In this sense, development systems that promote localizing the compaction caused by tires are being systematically explored. GNSS systems, combined with precision agriculture technologies, have mainly influenced the localized movement, developing Controlled Traffic Farming (CTF), which has proven viable in reducing crop trampling and localized compaction [21–23]. CTF is a system in which machines have shared or multiple working widths, concentrating soil compaction to the track lanes by optimizing route planning on farming operations [16,24].

CTF's essence is the elimination of soil compaction within the cultivated area, an increase in traction efficiency on permanent roads, and improved crop yields and economic returns, making it a promising solution for farmers [25]. CTF represents an excellent solution in this context, as traffic-induced soil compaction is lower, since the cultivation area is separated from the permanent traffic lanes [26].

CTF provides many benefits to crop systems, since greenhouse gas emissions are affected by plant performance and yield, as well as fertilizer and water use [27]; the technique can reduce the area covered by tires within the crops, a footprint between 40 and 60% of the area dedicated to each crop's production [28,29], compacting soil density only in the wheeled transit zone and reducing fuel consumption [30]. Positive changes influenced by CTF implementation can be significant for the world's leading crops, such as soybean. Since the operation is fully mechanized, traffic control can contribute to reducing the compacted area in the crop.

Machines' energy demand can be reduced when they travel over compacted surfaces, as demonstrated by Bertollo et al. [31], and consequently, pollutant emissions decrease; this contributes to sustainable agriculture and the mitigation of greenhouse gas emissions, mainly CO₂; emissions are a significant concern associated with agricultural intensification [32]. Sustainable development initiatives identify opportunities to reduce carbon emissions, decrease energy consumption, and improve operational efficiency [33].

An assessment of CTF, fuel demand, and polluting gas emissions is essential for the sustainability of modern agricultural systems. Therefore, this study evaluated fuel consumption and CO₂ emissions at different CTF intensities in bare soil and with straw cover on land used for soybean cultivation.

2. Materials and Methods

2.1. Study Site and Experimental Design

The study was conducted at the Mato Grosso do Sul State University (19°05'29" S, 51°48'49" W, and altitude of 535 m). According to Köppen, as adapted by Alvares et al. [34],

the region's climate is characterized by a rainy summer and dry winter, with an average annual precipitation level and temperature of 1520 mm and 24.1 °C, respectively.

The soil has been classified as Quartzarene Neosols, according to Santos et al. [35], and as Entisols (Quartzipsamments) according to Soil Taxonomy [36]. The water content used was $20 \pm 1\%$; this water content was selected based on its approximation to the soil's friability point.

The treatments comprised three soil preparation systems and three soil compaction levels associated with the agricultural tractor. The soil preparations were conventional tillage (bare soil), soil till over millet straw, and soil till over brachiária straw, and subplots consisted of three levels of compaction by the agricultural tractor on the same traffic line: 2, 4, and 8 passes (steps).

Conventional soil tillage was carried out with a plowing harrow, model GAICR (TATU Marchesan—Matão, Brazil), with 16 concave cutting discs 26" diameter, spaced at 270 mm, and a cutting width of 2000 mm, and a leveling harrow, model NVCR (Baldan—Matão, Brazil), with 28 discs (14 front cut discs with 22" diameters and 14 smooth rear discs with 20" diameters) spaced at 175 mm, with a cutting width of 2350 mm. One plowing harrow-pass and two leveling harrow-passes replicated the standard procedure adopted in conventional tillage.

Soil conservation management was implemented by planting desiccating cover crops and quantifying the plant material on the soil. In tillage on millet straw, the desiccation area was covered with millet straw (6.65 Mg ha^{-1}); in the till on brachiária straw, the desiccation quantity was (10.07 Mg ha^{-1}). Each experimental unit (subplot) was 4.5 m wide by 25 m long.

Additional compaction in a CTF traffic line was created in the field using an agricultural tractor, model 4×2 TDA, with 62.5 kW engine power and equipped with Pirelli front tires, model TM95 bias ply construction, and rear tires of 14.9–24 Goodyear model Dyna Torque II bias ply 18.4–34; the total tractor mass was 3900 kg. This tractor passed over traffic lines 2, 4, and 8 times (passes), simulating the various traffic machines used in the crop throughout the soybean cycle.

After the plot's traffic lines were determined, the soybean cultivar Brasmax Tanque I2X was sown. Soybean seeds previously treated with fungicide and insecticide were inoculated with *Bradyrhizobium japonicum* strains Semia 5079 and Semia 5080. According to the recommendation for this cultivar, the row spacing was 0.45 m, and the sowing density was 15 seeds per meter. The seeder had five sowing lines and a total mass of 1145 kg. All sowing plots were covered at a constant speed of 5 km h^{-1} with the same mechanized set.

Phytosanitary management in the experimental plots followed the procedures adopted in commercial farming, including fertilization, the monitoring of pests and diseases, and the chemical control of weeds. All products were applied identically to all plots. After the complete soybean development cycle, 120 days after sowing, the plots were harvested to measure total productivity. Figure 1 describes the procedure adopted during the research.

2.2. Data Collection and Statistical Analysis

The tractor's hourly fuel consumption (L h^{-1}) was determined using two flowmeters from the Oval brand, model type LSF41, with a 1 mL/pulse resolution. The flow meters were installed in the tractor engine's supply and return lines. The different pulse signals generated by the flowmeters determined fuel consumption in the programmable logic controller (PLC), generating the hourly fuel consumption, as determined according to Equation (1).

$$CCh = \frac{\sum (pe - ps) \cdot 3.6}{\Delta t} \quad (1)$$

where CCh = hourly fuel consumption (L h^{-1}); $\sum (pe - ps)$ = differences in the flowmeters' pulses entering and returning from the engine; Δt = time spent on the installment (s); and 3.6 = conversion factor.

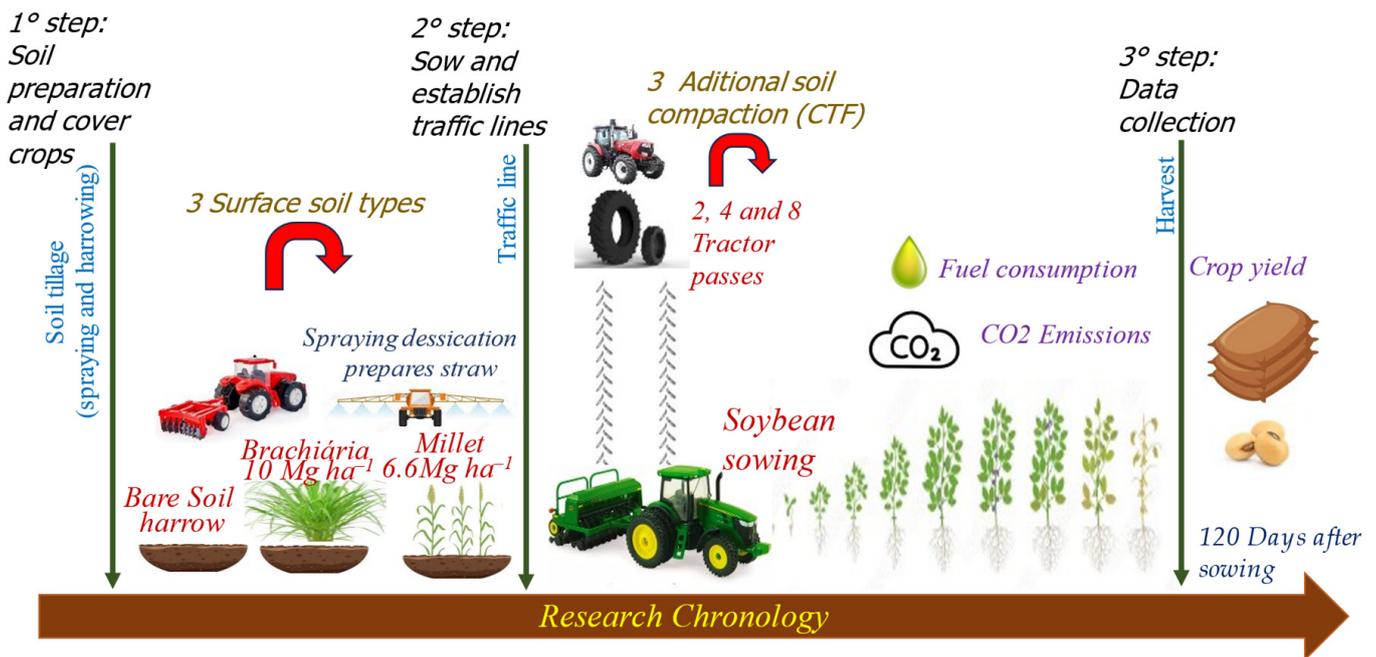


Figure 1. Details of the research scheme.

The relationship between the area of the plot and the time spent traveling determined effective field capacity by the terms of Equation (2).

$$CE = \frac{Atr}{\Delta t} \cdot 0.36 \tag{2}$$

where CE = effective field capacity ($ha\ h^{-1}$); Atr = useful area of the worked plot (m^2); Δt = time spent traveling the experimental plot(s); and 0.36 = conversion factor.

The operational fuel consumption, which represents the fuel consumption per specific area worked, was obtained by means of Equation (3).

$$COC = \frac{Cch}{Cce} \tag{3}$$

where COC = operational fuel consumption ($L\ ha^{-1}$); Cch = fuel consumption per hour ($L\ h^{-1}$); and Cce = effective field capacity ($ha\ h^{-1}$).

The determination of the carbonic gas emissions (CO_2) from the agricultural tractor engine was carried out based on the fuel consumption in each treatment and the established ratio of 1: 3.76, in that each liter of Diesel oil burned in the engine can emit 3.76 kg of carbon dioxide (CO_2), as described by [37,38].

Soybean productivity was determined 120 days after sowing, when the plants reached full maturity. All plants in the utilized subplot area were manually harvested and threshed, and the degree of humidity was determined. Subsequently, this was corrected to 13% humidity and the productivity extrapolated to $kg\ ha^{-1}$.

The experimental design used involved randomized blocks in a split-plot scheme with four replications. Three soil preparation systems were considered: conventional bare soil, a millet straw preparation, and a brachiária straw preparation. They were divided into subplots of 3 compaction levels by agricultural tractor: 2, 4, and 8 passes. The results were subjected to the Anderson–Darling normality test and subsequently submitted to variance analysis (ANOVA). Their means were compared using the Tukey test at a significance level of 5%. Minitab 16 software was used for all statistical analysis of data.

3. Results and Discussion

The results show that an increased number of tractor passes reduces fuel consumption, regardless of the level of vegetation soil cover (Figure 2). Compared to the lowest compaction level (two passes), eight passes showed a 25% reduction in the tractor's fuel consumption. Assessments of different levels of cover showed that areas without vegetation cover (bare soil) have high fuel consumption (15.5 L h^{-1}). Millet straw as soil cover increased density and reduced energy demand in situations of mechanized operation. Coverage with millet and brachiária did not differ statistically.

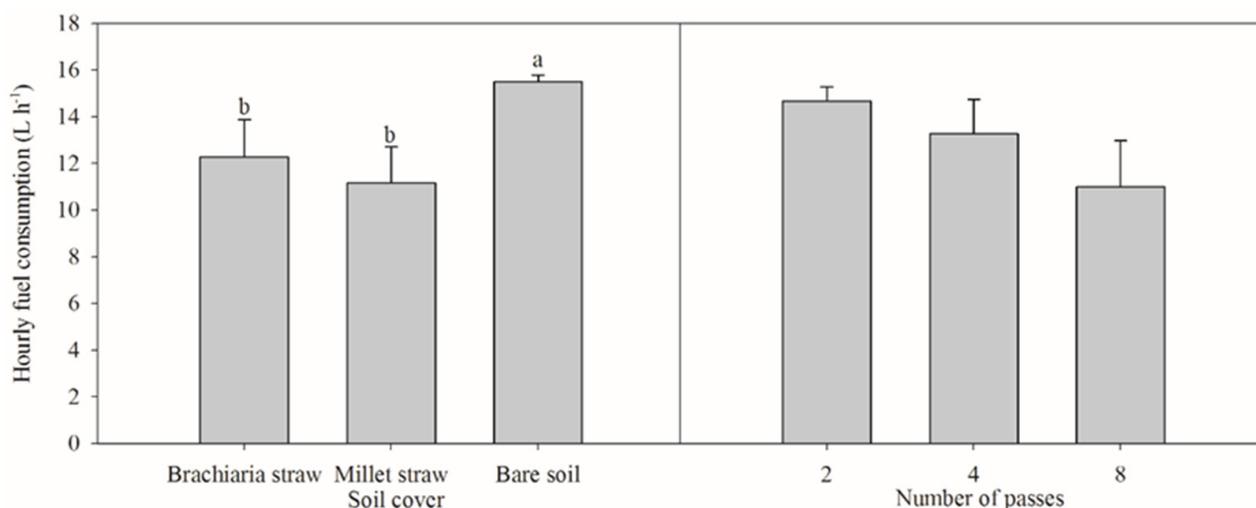


Figure 2. Hourly fuel consumption in soybean sowing. Means associated with identical letters on the bars do not differ by the Tukey test ($\alpha = 5\%$).

After the machine passes over the location precisely between the crop rows, relocated soil particles reduce macroporosity in the traffic zone. Rigid surfaces tend to support greater loads and increase the machines' traction. An increased number of machine passes creates surface soil compaction, reducing the machine's rolling resistance and lowering fuel consumption [39]. Thus, the ground imposes more reaction forces with well-defined traffic lines, deforming less, and reducing the machine's rolling resistance and fuel demand [22].

The absence of vegetable cover had a detrimental effect on the machines' energy consumption. The highest hourly fuel consumption (L h^{-1}) was observed on bare ground, primarily due to the lower reactive forces of the ground around the wheelsets, which caused more significant deformations and rolling resistance. Marques Filho et al. [19] suggested that vegetation cover on the ground can effectively alleviate the stress caused by wheelsets. Providing larger contact areas and reduced footprint depths potentially offers a solution to the problem of reducing machine fuel consumption. Furthermore, increasing soil density in the wheeled transit zone can reduce machine slippage, providing a lower energy demand, in terms of fuel.

Vegetation crop coverage reduces the wheelset's impact on the soil and tractor fuel consumption, as compared to conventional tillage systems [40,41]. The vegetation cover is a mitigating agent with respect to the machine's impact on the ground, because the contact area increases, and a reduced wheelset pressure is applied. Marques Filho et al. [19] show that in agricultural areas, straw on the surface acts as a mattress between the soil and the wheelset, increasing the contact area and reducing the pressure applied to the ground. However, our results show that the localized application of loads between the rows increases compaction in the surface zone of the soil by relocating the straw.

Fuel consumption differed statistically between the analyzed conditions. The soil without vegetation cover was associated with the highest levels of rolling resistance and operational energy demand (Figure 3). The operational fuel consumption shows that the conventional preparation (bare soil) presented the highest consumption (21 L ha^{-1}); in

treatments with soil vegetation cover, specifically, brachiária and millet, the consumption levels were (16 and 15 L ha⁻¹), respectively. Gozubuyuk et al. [42] observed that straw cover reduced operational fuel consumption, which corroborates this research; the authors obtained liters per hour fuel savings of 3.5-fold compared to areas without vegetation cover. Conservation tillage practices, especially no-till practices, generally reduce fuel consumption, compared to conventional tillage [43].

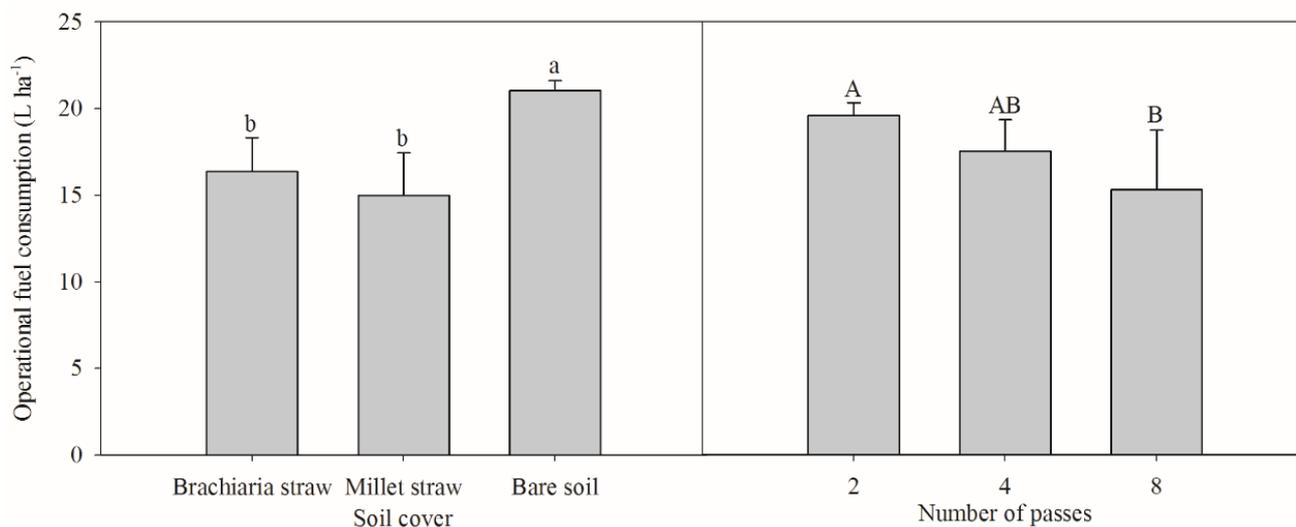


Figure 3. Operational fuel consumption in soybean sowing. Means associated with identical letters on the bars do not differ by the Tukey test ($\alpha = 5\%$).

Statistical differences were observed in several agricultural tractor passes, with two passes showing higher consumption than the treatment with eight passes. Furthermore, with four passes, there were no differences between treatments.

Fuel consumption per hectare is a parameter useful for comparing farming operations in different countries, as it indicates the fuel demand based on the area worked [38]. However, factors such as relief, soil type, and machine characteristics must be considered for a more accurate analysis.

The results show that the lowest operational fuel consumption (15.3 L ha⁻¹) is associated with the treatment with eight agricultural tractor passes, a compacted traffic line that requires less engine torque, improving energy performance in controlled traffic [44]. In addition, according to Martins et al. [45], operational fuel consumption is related to the equipment width and operating speed; so, with more significant passes, there is greater definition to the lanes and less agricultural tractor rolling resistance.

Fuel consumption showed statistical differences linked to vegetation cover type and the tractor's passing over the crop line, which indicates that these variables affect the energy demand of agricultural operations. Controlling energy consumption factors in crops is imperative due to their impact on an agribusiness's total cost and sustainability. According to Martins et al. [46] and Lopes et al. [47], the machine's travel speed, engine speed, and terrain surface can affect fuel consumption.

Better management of fuel consumption during the production process, as well as factors associated with the operation, such as terrain, soil characteristics, production systems adopted, and machine conditions used in the field, can contribute to more ecological and sustainable production standards [48].

Fuel consumption directly affects greenhouse gas emissions. Therefore, CTF represents an alternative capable of mitigating adverse environmental effects. The increase in traffic line passes promoted a reduction in CO₂ emissions (Figure 4), with eight passes on the controlled traffic line producing the lowest amount of CO₂ (41.3 kg h⁻¹).

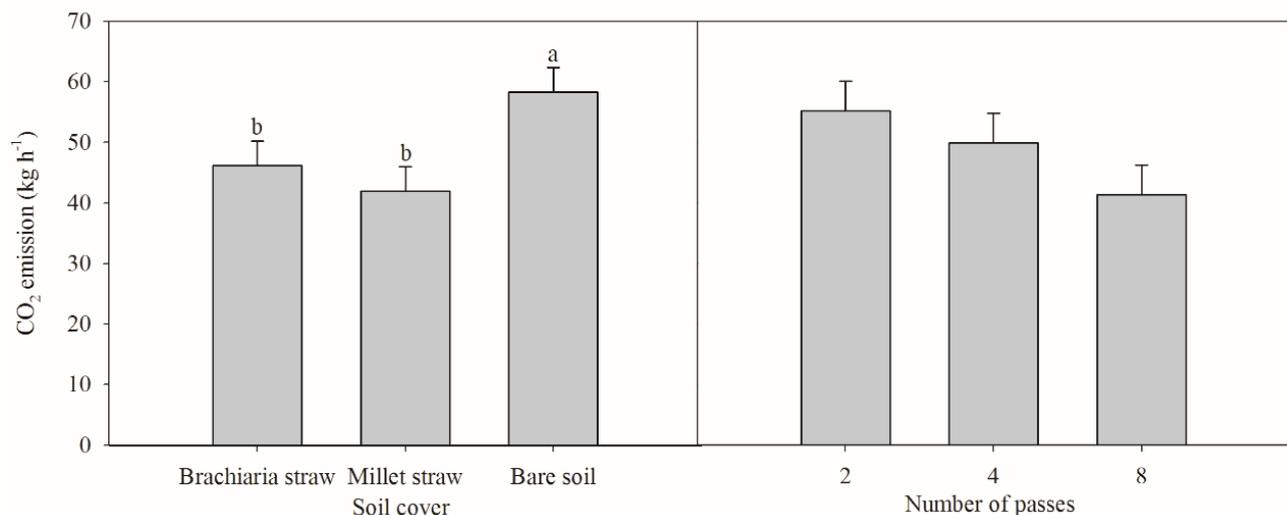


Figure 4. CO₂ hourly emissions in soybean sowing. Means associated with identical letters on the bars do not differ by the Tukey test ($\alpha = 5\%$).

Traditional soil management, which maintains an unprotected surface, reduces biological plant root development. Furthermore, bare soil deforms intensely, increasing rolling resistance and promoting a more significant environmental impact of mechanization. Conventional soil management resulted in higher CO₂ emissions (58.3 kg h⁻¹) than did the use of brachiária and millet (46.1 and 41.9 kg h⁻¹, respectively). Considering CO₂ emissions per hour, we found that brachiária straw and millet reduce them by 20% and 28%, respectively, compared to bare soil.

Controlled traffic effects improve traction efficiency, reduce rolling resistance, and reduce planting slippage, thus mitigating CO₂ emissions. Strategies adopted by producers to increase energy efficiency, such as introducing precision agriculture technologies, can significantly contribute to the reduction of emissions, since emissions from tractors are commonly unknown or are disregarded in technical analyses, reinforcing the fact that this issue still needs to be explored in depth [49].

By extrapolating CO₂ emissions per cultivated area (Figure 5), it can be determined that high CO₂ emissions per hectare are evident in places with lower tractor traffic intensity (two and four passes; 73.5 kg ha⁻¹) and bare soil (79.1 kg ha⁻¹). Our findings differ from Šarauskiš et al. [38], who analyzed fuel consumption and CO₂ emissions in different strip cultivation scenarios and obtained significantly different results for hourly CO₂ gas emissions and CO₂ per hectare emissions.

Increasing the traffic line from two to eight passes generated a 21.6% reduction in CO₂ emissions, demonstrating that adopting controlled traffic contributes to a more sustainable agriculture (Figure 5). According to Damanauskas and Janulevičius [50], scientists need to work with farmers to develop technologies to increase the efficiency of agricultural machinery and reduce emissions, as presented in this research. In this manner, controlled farm traffic can increase crop productivity and reduce common externalities in agricultural production. New concepts of sustainable agriculture and payment models for ecosystem services can be designed to benefit crops that adopt CTF.

Vegetation cover on the soil surface reduced CO₂ ha⁻¹ emissions by 22.2% in brachiária and 28.6% in millet, compared to bare soil. In addition to helping with tractor performance and mitigating emissions, straws benefit the soil structure and can optimize crop production, showing that this technique helps the agriculture industry to reduce pollutant emissions. Management practices considering permanent soil cover in tropical agriculture are essential for maintaining productivity and reducing environmental impacts. In tropical regions, the water regime is associated with a strong potential for erosion and soil impoverishment.

No-till practices can reduce emissions by 20.6–23.7%, compared to conventional tillage [51].

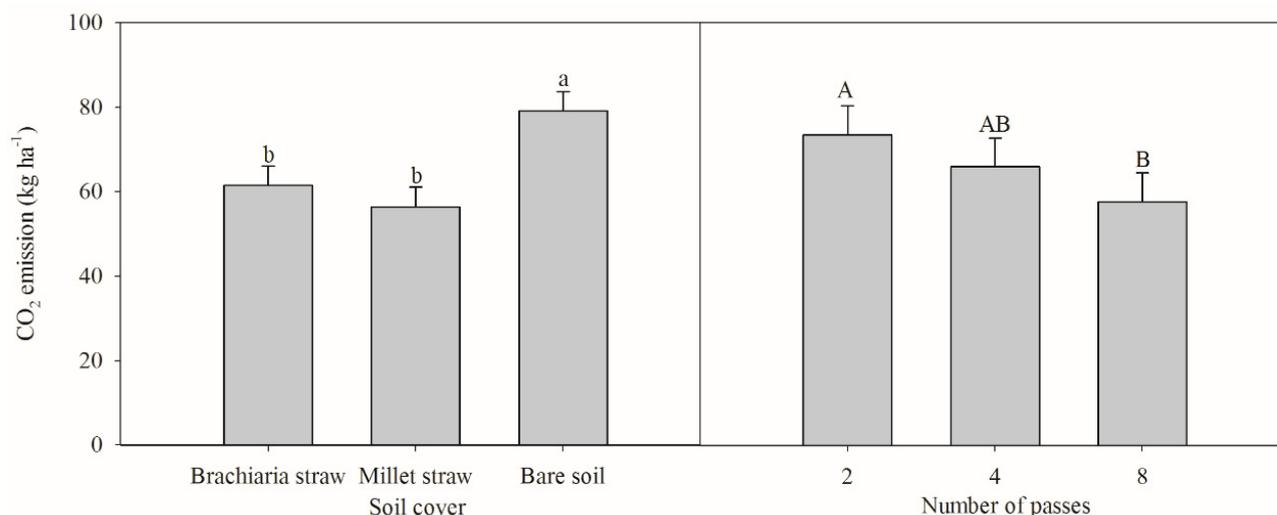


Figure 5. CO₂ per hectare emissions. Means associated with identical letters on the bars do not differ by the Tukey test ($\alpha = 5\%$).

Gozubuyuk et al. [42] investigated yield performance and CO₂ emissions under different sowing practices and crop rotations. They found a 137.4 kg CO₂ ha⁻¹ reduction in CO₂ emissions from conservation tillage with vegetative soil cover, as compared to cultivation without straw, resulting in a 71.4% reduction in CO₂ emissions; these practices should be encouraged to provide fuel savings and highly environmentally friendly agricultural production.

In addition to practices such as cover crops, crop rotation has been associated with increasing soil organic carbon stocks and reducing CO₂ emission rates. It contributes to carbon sequestration and increases soil resilience to climate change and intensive agricultural activities, optimizing plant productivity [52,53]. This relationship is particularly vital in global food security, as sustainable agricultural practices that improve soil health can lead to agricultural systems which are more productive and resilient [54].

Soybean productivity did not show a statistical difference associated with vegetation cover type (Figure 6). However, there was a tendency for greater productivity in covered soil conditions. Our results agree with those obtained by Godwin et al. [17], in which soils with straw present better productive performance.

Among vegetation cover systems, brachiária provided greater productivity, at 3876 kg ha⁻¹, followed by millet with 3583 kg ha⁻¹. However, the lowest productivity was seen without straw, at 3572 kg ha⁻¹. Vegetation coverage affected soybean productivity, increasing it by 7.84% compared to the highest productivity, which was obtained in brachiária straw; the lowest performance was associated with bare soil. In this way, vegetation cover presence increased productivity, especially in brachiária, which may be related to straw soil being favorable for the plant's water supply. In addition, grasses belonging to *Urochloa* (synonym Brachiária) have bulky and aggressive roots, optimizing the soil conditions [55]. This prompts a physical process in which the aggressive and voluminous brachiária roots drag other nearby roots to greater depths. This allows the crop intercropped with this grass to perform in a superior manner.

Millet has a very aggressive root system and can reach great depths in the soil [56]. These characteristics improve the rhizosphere environment when millet is included in crop rotation systems, benefiting soil properties and species yield in succession [57].

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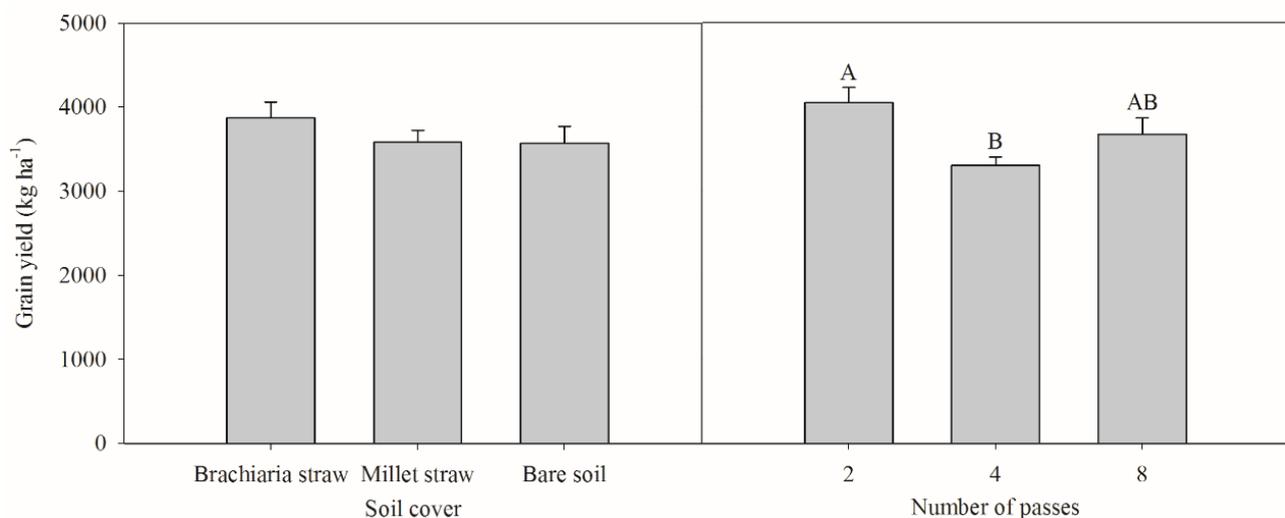


Figure 6. Soybean productivity. Means associated with identical letters on the bars do not differ by the Tukey test ($\alpha = 5\%$).

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Our study on the relationship between traffic intensity and productivity has practical implications. Wheels inevitably impact agricultural soils. We verified that the best production performance was achieved with 4.047 kg ha^{-1} with two passes in the area; this led to less compaction due to lower traffic intensity, which likely facilitated better root development. However, our results showed the lowest performance with four machine passes, increased to eight passes over the traffic line in zones with active CTF. Underground pressure bulbs can increase resistance to soil penetration in the zone of plant root development in conditions of four passes, concentrating the distribution of loads in the root zone. With eight passes, the loads are dissipated in depth [58,59], reducing the effect on the root system, as the traffic lanes are more defined. Without traffic, better root development due to the lower resistance to soil penetration and the consequent presence of roots in larger areas and at greater depths can guarantee better water and nutritional conditions for plants, as these conditions increase the root exploration area, allowing easy access to water and nutrients stored in the deeper layers of soil, increasing productivity [60,61]. Alakukku [62], in a clarifying review, describes the fact that the increasing passing of machines on mineral soils increases compaction in the subsoil. The CTF effect over time is significant and consistent, producing a throughput 4% higher than that of conventional traffic [17]. These findings can guide agricultural practices, which suggests that the reduction in traffic intensity can improve productivity [22]. Controlled traffic increases soils' physical quality and facilitates plants' access to water and nutrients, which can increase crop productivity [29]. However, our results showed the lowest performance with four machine passes over the traffic line in active CTF zones.

Our results differ from those of Girardello et al. [63], who found no difference in soybean productivity under controlled traffic with different intensities, and [12], who

found that strip compaction did not change soybean productivity. However, due to the high variability of results under field conditions, it is imperative to emphasize that even percentage differences in increased productivity significantly improve the productive agricultural process. Many researchers have not found statistically significant differences; nonetheless, the increased percentage values are equally important, as they increase the activity's profits.

Consistent with our research results, Godwin et al. [17] concluded that a soil conservation system with straw soil maintenance has a positive long-term effect on crop productivity and reduces crop implementation costs.

Therefore, CTF adoption, in combination with a no-till system, can be a profitable alternative to compacting the soil locally and improves soil structure in order to increase crop productivity [64]. Our results open possibilities for investigation in several CTF areas, as it is necessary to adequately understand the dynamics between ground and machine traffic, investigate machine routing technologies, and investigate load distributions underground around transit lines. Furthermore, precision agriculture techniques and production models with less impact on the soil can increase environmental crop efficiency and mitigate global environmental problems [23].

4. Conclusions

Differences in mechanized system performance were observed due to soil coverage and compaction intensity. The increased number of machine passes reduced fuel consumption and carbon dioxide (CO₂) emissions in all soil management types. CTF reduces machine rolling resistance and increases crop environmental efficiency.

Bare-soil areas show increases of 20.8% and 27.9% in hourly fuel consumption, compared to systems with brachiária and millet straw cover. Brachiária and millet straw reduce CO₂ emissions per hectare by 20% and 28%, compared to bare soil. Lower traffic intensities (two passes) resulted in (13.72%) higher soybean yields (of 4.04 Mg ha⁻¹).

Our research evaluated the effects of different traffic intensities on soybean crops in controlled conditions; however, new research must be developed to clarify whether these effects are maintained in different soils and with other mechanized agricultural operations.

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