INTEGRATION OF VARIABLE-RATE NITROGEN FERTILIZATION AND PERMISSIBLE TRAFFIC INTENSITY THRESHOLDS FOR SITE-SPECIFIC MANAGEMENT IN MECHANIZED SUGARCANE SYSTEMS

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Abstract

Precision Agriculture (PA) has traditionally focused on site-specific input management to improve fertilizer-use efficiency. However, in highly mechanized cropping systems such as sugarcane, soil physical degradation induced by machinery traffic remains an important constraint on system performance. This study analyzes two complementary approaches developed in commercial sugarcane production systems in Colombia: (i) variable-rate nitrogen fertilization (VRT), evaluated in terms of its operational performance, and (ii) a maximum permissible traffic intensity model (IT_{max}), proposed as a support tool for machinery traffic management. Variable-rate nitrogen fertilization was analyzed using operational records collected in six commercial sugarcane fields over four consecutive production years. The analysis focused on the correspondence between prescribed and applied doses under commercial conditions and compared VRT with a fixed-rate reference scenario defined as the uniform maximum nitrogen requirement within each field. The results showed operational efficiencies above 96% in all evaluated fields and reductions in nitrogen application ranging from 5.8% to 13.9% relative to the fixed-rate scenario. In addition, VRT substantially reduced the spatial extent of nitrogen overapplication. Correlation analyses between yield indicators and spatial parameters associated with nitrogen recommendation maps suggested that greater spatial differentiation in nitrogen application could be associated, in some fields, with more favorable yield indicators. Complementarily, mechanized harvesting operations with self-unloading wagons were analyzed to evaluate the relationship between traffic intensity and soil compaction. Soil penetration resistance (PR) and wet bulk density (WBD) were evaluated under different traffic intensities and initial soil conditions. PR was more sensitive than WBD for detecting compaction induced by machinery traffic. Traffic intensities equal to or greater than 612.12 $Mg \cdot km \cdot ha^{-1}$ were associated with restrictive PR values in the surface layers, while compaction also showed lateral propagation beyond the directly trafficked area. These relationships allowed the definition of a maximum permissible traffic intensity threshold as a practical criterion for traffic management in mechanized sugarcane systems. Although both components were analyzed from independent datasets, their joint interpretation suggests that variable-rate fertilization and permissible traffic intensity thresholds can be understood as complementary tools within a broader precision agriculture framework. From this perspective, site-specific management in mechanized sugarcane systems may benefit from integrating decisions related to fertilization operations and the mechanical loads acting on the soil, contributing to both operational efficiency and soil physical functionality.

Keywords: Precision Agriculture, Variable-Rate Fertilization, Site-Specific Management, Traffic Intensity, Soil Compaction, Mechanized Sugarcane, Nitrogen Management.

1. Introduction

Precision Agriculture (PA) has become established as an approach aimed at improving resource-use efficiency through the site-specific management of agricultural inputs. Technologies such as variable-rate fertilization (VRT) have made it possible to adjust nutrient application according to spatial variability within fields, contributing to waste reduction and, in certain contexts, to improvements in crop agronomic response (Cai *et al*., 2025; Jalilian *et al*., 2025; Ruder *et al*., 2026). In crops such as sugarcane, characterized by highly mechanized production systems, VRT represents a relevant tool for optimizing nitrogen management under heterogeneous soil conditions.

In parallel, in these highly mechanized systems, machinery traffic is a determining factor in the modification of soil physical properties. Traffic-induced compaction has been widely recognized as a process that affects soil structure, porosity, and root development, with direct implications for crop performance. Soil compaction in sugarcane can reduce yield by approximately 20% to 47%, depending on the intensity of mechanized traffic and varietal susceptibility (Delmond *et al*., 2024; Liu *et al*., 2026). Indicators such as soil penetration resistance and bulk density are commonly used to characterize soil physical condition in terms of compaction, especially in systems that employ heavy equipment, as occurs in mechanized sugarcane harvesting (Saavedra-Rincon & Chaparro-Anaya, 2023).

Although both nutrient management and machinery traffic control have been addressed within the framework of Precision Agriculture, these components are often studied and managed independently. On the one hand, VRT focuses on optimizing the application of chemical inputs; on the other, machinery traffic analysis focuses on conserving soil physical conditions. However, both aspects represent fundamental dimensions of production system functioning and, together, condition its performance.

In this context, the concept of traffic intensity, expressed as the cumulative mechanical load applied to the soil per unit area, constitutes a useful metric for quantifying the impact of mechanized operations. The definition of permissible traffic intensity thresholds (IT_{max}) makes it possible to identify levels above which soil structural conditions may become restrictive for crop development. In sugarcane, critical bulk density values above 1.6 $Mg \cdot m^{-3}$ have been reported in medium- to fine-textured soils and associated with limitations to root growth (Reichert *et al*., 2009), as have soil penetration resistance values above 2.0–3.0 MPa, beyond which root elongation is significantly restricted (Taylor *et al*., 1966). These ranges provide reference criteria for interpreting the effects of machinery traffic and establishing operational limits in the field (Saavedra-Rincon & Chaparro-Anaya, 2023).

From this perspective, variable-rate fertilization and the definition of traffic intensity thresholds can be understood as complementary tools within Precision Agriculture, oriented toward managing different dimensions of the production system: fertilization and mechanical loads, respectively.

Accordingly, the objective of this study was to analyze two approaches developed in commercial sugarcane production systems—variable-rate nitrogen fertilization and a maximum permissible traffic intensity model—and to discuss their complementarity as the basis for a precision agriculture decision framework applied to highly mechanized systems.

2. Materials and Methods

2.1. Analysis of variable-rate nitrogen fertilization

The analysis of variable-rate nitrogen fertilization was carried out using operational application records collected in six commercial sugarcane fields located in Valle del Cauca, Colombia, over four production years. Together, the evaluated fields covered an approximate area of 66.7 ha, with individual areas ranging from 2.9 to 20.8 ha, corresponding to commercial sugarcane production units. These records correspond to real mechanized fertilization operations implemented under Precision Agriculture schemes in commercial conditions.

The nitrogen prescriptions used in the VRT operations were previously generated through agronomic procedures defined by the production system, considering the spatial variability of soil properties and technical crop management criteria. In this study, these prescriptions were assumed to be agronomically valid; therefore, the analysis focused exclusively on evaluating the operational performance of variable-rate application and not on validating the fertilization recommendation models. This approach is consistent with operational assessments of Precision Agriculture technologies under commercial production conditions.

The analyzed information included georeferenced data on prescribed and applied doses, which made it possible to evaluate the degree of agreement between them as an indicator of the operational efficiency of the variable-rate fertilization system. This approach is consistent with operational assessments of Precision Agriculture technologies under commercial production conditions (Saha *et al*., 2025).

To establish a reference scenario, a conventional fixed-rate fertilization scheme was constructed, defined as a uniform dose equivalent to the maximum nitrogen requirement identified within each field. This scenario represented a hypothetical management condition used to compare the performance of VRT against a conventional practice without spatial differentiation.

Nitrogen surplus analysis was performed by spatially comparing the doses applied under VRT with the corresponding dose in the fixed-rate scenario, allowing the potential reduction in fertilizer application associated with the use of variable-rate technology to be quantified.

Additionally, the relationship between variable-rate fertilization and crop response was evaluated using Pearson linear correlation analysis between yield indicators—tons of cane per hectare (TCH) and tons of sugar per hectare (TAH)—and the range of the geostatistical model used for interpolating (kriging) nitrogen doses, defined as the distance at which spatial dependence disappears, as a descriptor of the system's spatial structure.

Spatial and statistical analyses were conducted to identify patterns of association among soil variability, applied doses, and crop yield indicators under real management conditions.

2.2. Traffic intensity and soil compaction assessment

The analysis of traffic intensity and its relationship with soil compaction was performed using information collected during mechanized sugarcane harvesting operations in Valle del Cauca, Colombia. The evaluations were conducted on two soil areas of approximately 6,930 m^2 each, planted with sugarcane and composed of 35 rows with 1.65 m spacing and an average row length of 120 m. These areas made it possible to represent two contrasting conditions of initial susceptibility to compaction. The evaluations were carried out under commercial production conditions, using harvesting and transport equipment characteristic of the system, including a harvester, an accompanying tractor, and a self-unloading wagon.

The mechanized harvesting operation was planned using a system composed of a John Deere CH570 harvester, a CASE Puma 180 accompanying tractor, and a self-unloading wagon for receiving and transporting the harvested material. The tractor was equipped with R1W radial lug tires, size 710/70R38 on the rear axle, with an estimated contact area of 3140 cm^2, and 600/65R28 on the front axle, with an estimated contact area of 1915 cm^2. The self-unloading wagon was equipped with R1W radial lug tires, size 620/75R26, with an estimated contact area of 2320 cm^2. The harvester had an estimated track–soil contact pressure of 156.9 kPa. The tractor operated with tire inflation pressures of 103.4 kPa in the front tires and 158.6 kPa in the rear tires, while the self-unloading wagon had an inflation pressure of 296.5 kPa in both front and rear tires. According to the operational configuration represented, the harvester defined the main cutting and unloading trajectory of the crop, while the tractor–wagon set accompanied the operation and concentrated an important part of the traffic on the interrows. This condition was relevant for analyzing induced compaction because the magnitude and repetition of the loads applied by the equipment determined the cumulative traffic intensity on the soil.

In addition to the contact and inflation pressures, the machinery used in mechanized sugarcane harvesting was characterized by high power and load capacity. Mechanical harvesters commonly used in this type of operation have maximum engine powers of approximately 262.5 kW (352 hp) at 2,100 min^{-1} and operate at forward speeds close to 9 $km \cdot h^{-1}$. Their unloaded weight is around 184.42 kN, corresponding to an approximate mass of 18.50 Mg. The tractors used to pull the self-unloading wagons have powers close to 136 kW (182 hp) and an approximate weight of 127.49 kN, equivalent to a mass of 13 Mg. In turn, the self-unloading wagons used for receiving and transporting the harvested material have an unloaded weight of approximately 68.64 kN, equivalent to a mass of 7 Mg, and a load capacity of 107.87 kN, equivalent to a mass of 11 Mg. These magnitudes highlight the relevance of considering both machinery weight and repeated traffic when evaluating soil compaction during mechanized harvesting operations.

Traffic intensity was defined as the cumulative mechanical load applied to the soil per unit area, expressed in $Mg \cdot km \cdot ha^{-1}$. This indicator integrated equipment weight and the distance traveled over the affected area, allowing the level of mechanical intervention to which the soil is subjected during harvesting operations to be quantified operationally, in accordance with approaches that relate applied load and soil response (Håkansson & Reeder, 1994).

Traffic intensity was evaluated through treatments defined according to the cumulative number of equipment passes over the same soil surface during mechanized harvesting. The control represented the initial soil condition before the harvesting operation and therefore corresponded to a reference state without recent traffic from the harvester or the tractor–self-unloading wagon set. Treatments IT1, IT2, and IT3 represented increasing levels of machinery traffic: IT1 corresponded to two passes of the harvester, two passes of the tractor, and two passes of the self-unloading wagon over the same soil surface; IT2 corresponded to two passes of the harvester, three passes of the tractor, and three passes of the self-unloading wagon; and IT3 corresponded to two passes of the harvester, four passes of the tractor, and four passes of the self-unloading wagon. Thus, the treatments made it possible to contrast the initial soil condition with progressive scenarios of cumulative mechanical load associated with the harvester circulation pattern and repeated traffic of the tractor–wagon set over the same strip of the crop interrow.

For soil compaction characterization, two physical indicators were evaluated: soil penetration resistance (PR) and wet bulk density (WBD). PR was estimated in the field down to a depth of 50 cm, while WBD was determined down to a depth of 15 cm. These variables were selected as complementary indicators of soil physical condition under the loads induced by machinery traffic.

Measurements were taken at multiple points distributed within the evaluated fields, following a systematic sampling scheme along the interrows, with an approximate spacing of 15 m between sampling points and a total of eight sites per interrow. Geographic coordinates in a planar reference system were associated with each sampling point, enabling spatial analysis of the evaluated variables.

Additionally, basic soil physical conditions were characterized through the determination of texture, consistency limits, and critical moisture obtained from the standard Proctor test, in order to contextualize the soil response to machinery traffic. Moisture contents were expressed as gravimetric water content on a mass basis, reported as a percentage (%W). This characterization made it possible to differentiate two initial susceptibility conditions to compaction: a higher-susceptibility condition, associated with an initial WBD close to 1.56 $Mg \cdot m^{-3}$, corresponding to a loam-textured soil with a plastic limit of 25%W, liquid limit of 41%W, and critical moisture of 32%W; and a relatively lower-susceptibility condition, associated with an initial WBD close to 1.67 $Mg \cdot m^{-3}$, corresponding to a clay-textured soil with a plastic limit of 16.5%W, liquid limit of 39.8%W, and critical moisture of 21%W. In both cases, soil moisture conditions during the evaluations were close to the plastic limit, a condition that can favor mechanical deformation when the soil is subjected to repeated loads. Therefore, the observed response in terms of PR and WBD was interpreted by considering both cumulative traffic intensity and the initial soil physical condition.

The collected information was subsequently interpolated using geostatistical techniques (ordinary kriging), allowing the generation of continuous surfaces of the compaction indicators under the assumption of isotropy. This approach made it possible to analyze the spatial distribution of induced compaction before and after mechanized operations.

Based on the relationship between traffic intensity and PR and WBD values, soil response to different levels of mechanical intervention was evaluated, considering scenarios with multiple machinery passes and an initial reference state prior to mechanized harvesting. This analysis made it possible to identify compaction propagation patterns both in depth and horizontally.

Based on these results, a maximum permissible traffic intensity model (IT_{max}) was defined as the level of mechanical load above which compaction indicators exceed critical values for adequate functioning of the soil–plant system. This type of approach has been proposed as a strategy for sustainable machinery traffic management in intensive agricultural systems (Hamza & Anderson, 2005).

2.3. Spatial analysis and geostatistical modeling

Because the analyses of variable-rate nitrogen fertilization and traffic intensity were developed independently and using different datasets corresponding to different experimental conditions, no direct spatial integration between both variables was performed.

In this study, the relationship between both components was addressed through a complementary analysis approach, understood as the joint interpretation of results obtained from independent analyses, with the aim of discussing their influence on the behavior of the production system, without implying direct data integration or a causal relationship between the evaluated variables. This type of approach is consistent with systemic perspectives in precision agriculture, where different components of the soil–plant–machine system are analyzed independently but interpreted in an integrated manner for decision-making (Gebbers & Adamchuk, 2010).

This approach allowed the relationship between input-use efficiency, evaluated through variable-rate fertilization, and soil physical condition, influenced by machinery traffic intensity, to be interpreted as complementary factors in crop productivity, even though they were analyzed from independent experiments. Under this logic, the joint interpretation of both components allows their complementarity to be explored as support for decision-making in highly mechanized sugarcane systems.

3. Results and Discussion

The results are presented independently for the analyses of variable-rate nitrogen fertilization and traffic intensity, in accordance with the nature of the data and the experimental conditions under which they were developed. Subsequently, both components are interpreted complementarily in order to discuss their contribution to a decision framework for managing fertilization and mechanical loads in sugarcane systems under mechanized management.

3.1. Performance of variable-rate fertilization

The performance of VRT in the six evaluated fields was synthesized from operational records corresponding to four production years. For each field, the values presented in Table 1 correspond to the average of the four years of evaluation, calculated from the available annual information on recommended nitrogen, nitrogen applied under VRT, and nitrogen corresponding to the fixed-rate reference scenario. Average operational efficiency remained above 96% in all cases, indicating adequate execution of mechanized application and a high capacity of the system to reproduce spatial prescriptions in the field.

Table 1. Average operational performance of variable-rate nitrogen fertilization over four consecutive production years and comparison with a fixed-rate scenario in six commercial sugarcane fields.

Field	Area (ha)	Average recommended N per field (kg)	Average VRT-applied N per field (kg)	Average fixed-rate scenario N per field (kg)	Average operational efficiency (%)	Average reduction in application (%)
3102-094	2.9	950.3	934.7	1011.9	98.4%	7.6%
3106-480	20.1	7907.8	7746.4	8997.4	98.0%	13.9%
3109-400	8.1	3093.0	3094.8	3350.4	100.1%	7.6%
3111-110	4.1	1569.7	1563.4	1659.5	99.6%	5.8%
3111-132	20.8	8512.7	8508.3	9128.2	99.9%	6.8%
3426-020	10.1	3447.6	3340.7	3770.4	96.9%	11.4%

In terms of average nitrogen quantity per field during the four years of evaluation, the differences between recommended nitrogen and VRT-applied nitrogen were minimal in all cases, evidencing precise control of the dosage. For example, in field 3102-094, an average of 950.3 kg was recommended and 934.7 kg was applied, whereas in field 3111-132, the average values were 8512.7 kg recommended and 8508.3 kg applied. This behavior was consistently repeated in the other fields, reflecting the stability of the variable-rate application system.

The comparison with the fixed-rate fertilization scenario showed reductions in nitrogen application in all fields, with values ranging from 5.8% to 13.9%. This behavior is consistent with reports in the literature, where variable-rate fertilization reduces total input use relative to uniform schemes by adjusting doses to the spatial variability of the production system. In this sense, different studies have documented reductions in fertilizer use associated with the implementation of variable-rate application technologies, with magnitudes depending on the production context and system heterogeneity (Jalilian *et al*., 2025).

From a spatial perspective, the variable-rate fertilization operation showed a differentiated behavior compared with the fixed-rate scenario. Whereas the latter generates a homogeneous nitrogen distribution across the entire field, VRT allowed spatial application patterns to be reproduced in accordance with the internal variability of the system, adjusting doses to levels close to the recommendation in each management unit. This spatial differentiation was reflected in a substantial reduction in nitrogen surplus, understood as the amount of fertilizer applied above the recommended dose in each spatial unit. In the cumulative area of the six evaluated fields, surplus nitrogen was 500 kg under VRT, compared with 8847 kg under the fixed-rate scenario, representing an approximately 94% reduction over the four years analyzed. These results indicate that VRT reduced both the magnitude of surpluses and the risk of overapplication associated with the uniform scheme defined from the maximum requirements of the field.

In this context, the relationship between the spatial structure of fertilization—represented by the range of the geostatistical model (kriging)—and crop response in terms of yield was evaluated (Table 2). The results showed a predominance of negative correlations between the range and the yield indicators (TCH and TAH) in the analyzed fields.

Table 2. Pearson correlation coefficients between the range of the geostatistical model of nitrogen fertilization and crop yield indicators.

Field	TCH (t/ha)	TAH (t/ha)	r (TCH vs geostatistical range)	r (TAH vs geostatistical range)	Range (m)	Interpretation
3102-094	120.3	13.8	-0.7	-0.9	68.2	Strong negative correlation for TCH and very strong for TAH.
3106-480	126.0	16.1	-0.2	-0.2	258.1	Weak negative correlation for both indicators.
3109-400	128.3	15.2	-1.0	-0.5	119.8	Perfect negative correlation for TCH and moderate for TAH.
3111-110	125.5	13.9	-1.0	-1.0	79.5	Perfect negative correlation for both indicators.

These results show that the relationship between the range—as a descriptor of the spatial structure of the nitrogen variable—and the yield indicators presented a negative tendency in most of the evaluated fields, although with variations in the magnitude of association. This variability indicates that the degree of linear association between the spatial structure of fertilization and crop response was not uniform among the analyzed fields. In this context, the predominance of negative correlations suggests that greater spatial differentiation in nitrogen application could be associated, in some of the evaluated fields, with more favorable productive responses. Nevertheless, the variability observed among fields indicates that this relationship should be interpreted with caution and according to the specific conditions of each system, which is consistent with reports in the literature where variable-rate fertilization has been associated with both improvements in nutrient-use efficiency and increases in crop productivity under specific management conditions (Ruder *et al*., 2026).

3.2. Traffic intensity and soil response

Soil response to machinery traffic during the mechanized harvesting operation was conditioned by the characteristics of the initial physical properties, particularly WBD, which made it possible to identify two contrasting susceptibility conditions to compaction. A first condition, with initial values close to 1.56 $Mg \cdot m^{-3}$, presented greater susceptibility, while a second condition, with values close to 1.67 $Mg \cdot m^{-3}$, showed lower susceptibility associated with a more consolidated structural state.

The response to TI, evaluated through the control, IT1, IT2, and IT3 treatments, showed differentiated behavior between both conditions. As presented in Table 3, WBD remained within relatively narrow ranges regardless of the traffic level applied, indicating low sensitivity of this variable to changes induced by machinery traffic.

Table 3. PR response as a function of traffic intensity and initial WBD condition.

Initial WBD ($Mg \cdot m^{-3}$)	Treatment	TI ($Mg \cdot km \cdot ha^{-1}$)	Final WBD ($Mg \cdot m^{-3}$)	PR 0–10 cm (MPa)	PR 10–20 cm (MPa)	PR 20–30 cm (MPa)	PR 30–40 cm (MPa)	PR 40–50 cm (MPa)
≈ 1.56	Control	0	1.56	0.78	1.3	1.55	1.66	1.8
≈ 1.56	IT1	478.79	1.73	1.6	1.97	2.53	2.53	2.4
≈ 1.56	IT2	612.12	1.63	1.93	2.45	2.75	2.86	2.53
≈ 1.56	IT3	745.45	1.66	1.81	2.18	2.45	2.43	2.26
≈ 1.67	Control	0	1.67	0.66	1.03	1.33	1.86	2.05
≈ 1.67	IT1	478.79	1.7	1.06	1.47	1.84	2.28	2.5
≈ 1.67	IT2	612.12	1.7	1.11	1.59	2.02	2.1	2.15
≈ 1.67	IT3	745.45	1.69	1.04	1.41	1.82	2.38	2.48

In contrast, PR showed a clear response to increasing TI, evidencing differences between the control treatment and the treatments with traffic. This behavior confirms that PR is a more sensitive indicator of induced compaction than WBD.

Depth analysis allowed differentiated patterns in the vertical distribution of compaction to be identified. In the condition with lower initial WBD (≈ 1.56 $Mg \cdot m^{-3}$), treatments with higher TI levels promoted increases in PR to values equal to or greater than 2 MPa from the surface layers (<30 cm), indicating a rapid soil response to the application of mechanical loads. In contrast, in the condition with higher initial WBD (≈ 1.67 $Mg \cdot m^{-3}$), these values were reached predominantly in subsurface layers (>30 cm), indicating a greater capacity of the soil to buffer stresses in the surface layers.

Additionally, the spatial distribution of WBD and PR showed horizontal continuity among areas subjected to different TI levels. This indicates that the effect of machinery traffic was not restricted only to the directly trafficked zone but also influenced adjacent areas. Horizontal propagation of compaction reached a minimum value of 4.55 m in the condition with higher initial WBD, associated with lower susceptibility, and a maximum value of 18.77 m in the condition with lower initial WBD, associated with greater susceptibility. This result shows that traffic-induced compaction had a differentiated lateral expression according to the initial soil condition, being more extensive when the soil presented greater susceptibility to deformation.

The results show that compaction induced by agricultural mechanization responds to the interaction between TI and the initial soil condition represented by WBD, resulting in changes in PR magnitude, its depth distribution, and its horizontal propagation. The spatial continuity observed and the influence of TI on adjacent areas confirm that the effect of machinery traffic is not point-specific but expressed at the field scale.

Based on this behavior, a quantitative relationship between TI, PR, and WBD was established using a multiple linear regression model fitted by ordinary least squares (1). The values following the ± symbol represent the standard errors associated with the estimated regression coefficients:

$$IT = -(767.9 \pm 351.5) + (353.4 \pm 58.9) \cdot PR + (262.9 \pm 219.9) \cdot WBD \quad (1)$$

where IT is traffic intensity ($Mg \cdot km \cdot ha^{-1}$), PR is penetration resistance (MPa), and WBD is wet bulk density ($Mg \cdot m^{-3}$); therefore, Equation (1) is valid for these input units and yields IT in $Mg \cdot km \cdot ha^{-1}$.

The model explained approximately 50% of the variability in TI, showing that soil response to machinery traffic can be partially described from the interaction between its mechanical resistance and its initial structural condition. In this sense, PR acts as a sensitive indicator of the changes induced by mechanization, while WBD reflects the condition that modulates this response.

From an applied perspective, the proposed equation synthesizes the effects observed in the field and is presented as a tool for traffic management in mechanized agricultural systems, as it allows TI levels to be estimated from measurable soil conditions and operational thresholds oriented toward mitigating compaction to be established.

As an example of model application, for a soil condition characterized by a WBD of 1.5 $Mg \cdot m^{-3}$ and a PR value of 2.5 MPa—a threshold commonly associated with mechanical restrictions to root growth—Equation (1) estimates a maximum permissible traffic intensity (IT_{max}) of approximately 510 $Mg \cdot km \cdot ha^{-1}$. This value is close to treatment IT1 (≈ 478.79 $Mg \cdot km \cdot ha^{-1}$), which operationally corresponds to two passes of the harvester and two passes of the tractor–self-unloading wagon set, and is below the levels associated with IT2 (≈ 612.12 $Mg \cdot km \cdot ha^{-1}$) and IT3 (≈ 745.45 $Mg \cdot km \cdot ha^{-1}$), which involve two passes of the harvester combined with three and four passes of the tractor–self-unloading wagon set, respectively. In this sense, the model suggests that, under the evaluated conditions, traffic scenarios equivalent to IT2 and IT3 exceed the estimated threshold and could induce more severe compaction states, while management close to IT1 represents a critical intervention level from which the risk of soil compaction increases.

This behavior is consistent with reports in the literature, where PR values close to or above 2 MPa have been associated with limitations to root growth (Taylor *et al*., 1966), and where increasing traffic intensity during mechanized harvesting has been identified as one of the main factors of soil compaction (Delmond *et al*., 2024). Likewise, recent approaches in precision agriculture highlight the need to adjust mechanized operations according to soil physical conditions to minimize negative impacts on soil structure (Ruder *et al*., 2026).

3.3. Integrated interpretation of variable-rate fertilization and traffic intensity in precision agriculture

Precision agriculture has consolidated tools aimed at site-specific input management, particularly in the field of plant nutrition, where variable-rate fertilization has shown potential to improve nutrient-use efficiency and reduce environmental impacts associated with overapplication. Recent reviews agree that site-specific nutrient management is one of the most mature expressions of precision agriculture, insofar as it allows doses to be adapted to the spatial variability of the soil and crop, supporting more efficient and technically justified decisions (Cai *et al*., 2025; Vullaganti *et al*., 2025).

However, in highly mechanized production systems, such as sugarcane, decision-making cannot be limited only to the nutritional dimension. Crop response to applied inputs also depends on the soil physical condition, which can be significantly modified by repeated machinery traffic during harvesting and transport operations. Recent studies in sugarcane have shown that mechanized harvesting is an important source of compaction, capable of increasing soil penetration resistance, altering soil physical functionality, and compromising root growth and crop yield (da Luz *et al*., 2023; Delmond *et al*., 2024).

From this perspective, the results obtained in this study suggest that variable-rate fertilization and the definition of traffic intensity thresholds can be interpreted as complementary tools within the same precision agriculture framework. While the former guides fertilization management according to the spatial variability of the system, the latter provides criteria for regulating the mechanical loads acting on the soil and conditioning the physical medium in which the crop response to inputs must be expressed. Consequently, both dimensions can be understood as components of the same site-specific decision logic, in which it is not only important to determine how much input to apply and where, but also under what level of mechanical intervention soil functionality can be maintained.

This approach is consistent with recent perspectives that propose moving from a fragmented view of precision agriculture toward more integrated management schemes, where operational efficiency and soil physical quality are considered jointly (Ferraz Dias Neto *et al*., 2025). In the case of sugarcane, this approach is particularly relevant because the potential benefit of a spatially differentiated fertilization recommendation may be limited if the soil presents physical restrictions induced by excessive traffic. Therefore, a precision agriculture decision framework for mechanized sugarcane systems should simultaneously consider indicators associated with nutrient management and traffic intensity in order to prioritize agronomically efficient and physically viable interventions (Vullaganti *et al*., 2025; Ferraz Dias Neto *et al*., 2025).

In this sense, the conceptual proposal derived from this work does not imply a direct causal integration between the variables analyzed, but rather a complementary interpretation of two critical dimensions of the soil–plant–machine system. From this perspective, precision agriculture in sugarcane can move from approaches predominantly centered on variable input dosing toward a broader decision framework oriented toward the joint management of fertilization and mechanical loads as support for operational planning and conservation of soil physical quality.

4. Conclusions

Variable-rate nitrogen fertilization showed a high level of operational performance under commercial sugarcane production conditions, evidenced by the high agreement between prescribed and applied doses, as well as by the reduction in total nitrogen application relative to a fixed-rate scenario. These results confirm its usefulness as a precision agriculture tool for improving the operational precision of fertilization management in heterogeneous systems.

Compaction induced by mechanized harvesting responded to traffic intensity and the initial soil physical condition, mainly affecting soil penetration resistance and its vertical and horizontal distribution. In this context, PR was established as a more sensitive indicator than WBD for identifying changes induced by machinery traffic and for establishing operational intervention thresholds.

The maximum permissible traffic intensity model represents a tool with applied potential for traffic management in mechanized systems, as it allows measurable soil conditions to be linked with critical levels of mechanical load. Its use may contribute to reducing compaction risk and guiding operational decisions more closely adjusted to soil physical functionality.

Overall, this study suggests that precision agriculture in sugarcane can benefit from a broader view of site-specific management, in which variable input dosing and mechanized traffic control are considered complementary dimensions of the soil–plant–machine system. From this perspective, the joint management of fertilization and mechanical loads is proposed as a useful conceptual basis for supporting decision-making in highly mechanized agricultural systems.

Future studies should jointly evaluate nutritional and traffic variables on the same spatial support in order to advance toward the operational validation of integrated decision frameworks in precision agriculture for sugarcane.

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