FIELD-BASED EVALUATION OF TARGETED HERBICIDE SPRAYING EFFICACY : A COMPARISON OF QUALITATIVE AND QUANTITATIVE APPROACHES

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ABSTRACT:

Weed control remains one of the main challenges for maintaining agricultural productivity. In this context, selective spraying based on optical sensors and embedded vision systems emerges as a promising alternative for localized weed management, aligned with the principles of precision agriculture and sustainability. However, the adoption of these technologies on a commercial scale demands robust methods to evaluate agronomic efficacy and operational performance under real field conditions. This study aimed to establish methods to evaluate the effectiveness of spraying systems in herbicide applications, using glyphosate as a control tool. Two independent trials were conducted in an experimental area of 1.2 ha. The first trial evaluated the application over the entire area, while the second trial evaluated the localized application, both carried out at three travel speeds: 8, 10, and 12 km h^{-1}. A self-propelled sprayer with a precision spraying system was used, maintaining a constant application rate of 200 L ha^{-1} and a working pressure of 4.5 bar for the "Green on Brown" spraying. In this work, when comparing the traditional spraying methods over the entire area with a localized application system, it is estimated that there was a 99.5% gain in terms of spray consumption per area size, which demonstrates the potential for incorporation into spraying prior to planting crops of great economic interest. The efficacy evaluation was carried out qualitatively, traditionally visually for each repetition of the treatments, and quantitatively using the VARI (Visible Atmospherically Resistant Index), where the maximum and minimum values of the index were collected. Both assessments were performed 7 and 14 days after application (DAA). The results indicate that in the qualitative assessment at 7 DAA there was no significant difference (ANOVA, $p = 0.49$) between treatments, while at 14 DAA all treatments had the same estimated efficacy. In the quantitative assessment with VARI data (minimum values), the result shows a statistically significant difference for the broadcast application method at 7 DAA (Kruskal-Wallis, $p < 0.1$) and a statistically non-significant difference for spot application at 14 DAA (Kruskal-Wallis, $p = 0.12$) with a significance level of 5%. It was concluded that alternative efficacy quantification indices/methods that allow for equivalence with the qualitative assessment may be employed in the future.

INTRODUCTION:

Control of weeds continues to be one of the main challenges for maintaining agricultural productivity. However, the conventional application of herbicides over the entire area (broadcast) is often associated with excessive pesticide use, increased operational costs, and potential environmental impacts. In this context, precision agriculture emerges as a tool capable of integrating technologies and data (Inamasu et al., 2011; ISPA, 2023).

Among the innovations for localized weed management, targeted spraying stands out, which consists of cameras, optical sensors, computer vision systems, and solenoid valves (PWM - Pulse-Width Modulation) to apply herbicides only to the detected weeds (Rajuroy, 2025; Becker et al., 2021). However, the large-scale adoption of these technologies depends not only on the efficiency of detection algorithms but also on the quality of application, pesticide deposition on the target, the agronomic efficacy and control.

Alongside technological advancements, there is a growing effort to develop standardized methods for evaluating targeted spraying. Initiatives led by organizations such as ASABE (American Society of Agricultural and Biological Engineers) have proposed specific protocols for assessing targeted application systems, including metrics for coverage, deposition, and performance under controlled and field conditions (ASABE, 2025; Barlow, 2025a; Barlow, 2025b). However, despite these normative advancements, gaps still exist regarding the application of these methods in real operational conditions, especially in self-propelled sprayers equipped with commercial target spray systems.

Considering this scenario, the need for studies that integrate application technology, operational parameters, and quantitative efficacy evaluation methods becomes evident, especially in field trials. Thus, the present work aims to establish methods and parameters to evaluate the targeted weed management applications in comparison to broadcast equivalence using self-propelled sprayers.

MATERIALS AND METHODS

The experiments were conducted at Bayer's Innovation Hub in Paulínia, SP, in a total area of 1.2 hectares, with the planting of Brachiaria *ruziziensis*, aiming to evaluate the effectiveness of spraying systems in herbicide applications at different operating speeds. The herbicide used in both trials was a mix of glyphosate (3 L ha^{-1}) and adjuvant Aureo (1 L ha^{-1}), employed as an indicator tool for the product's action over time, allowing the assessment of the control response after application.

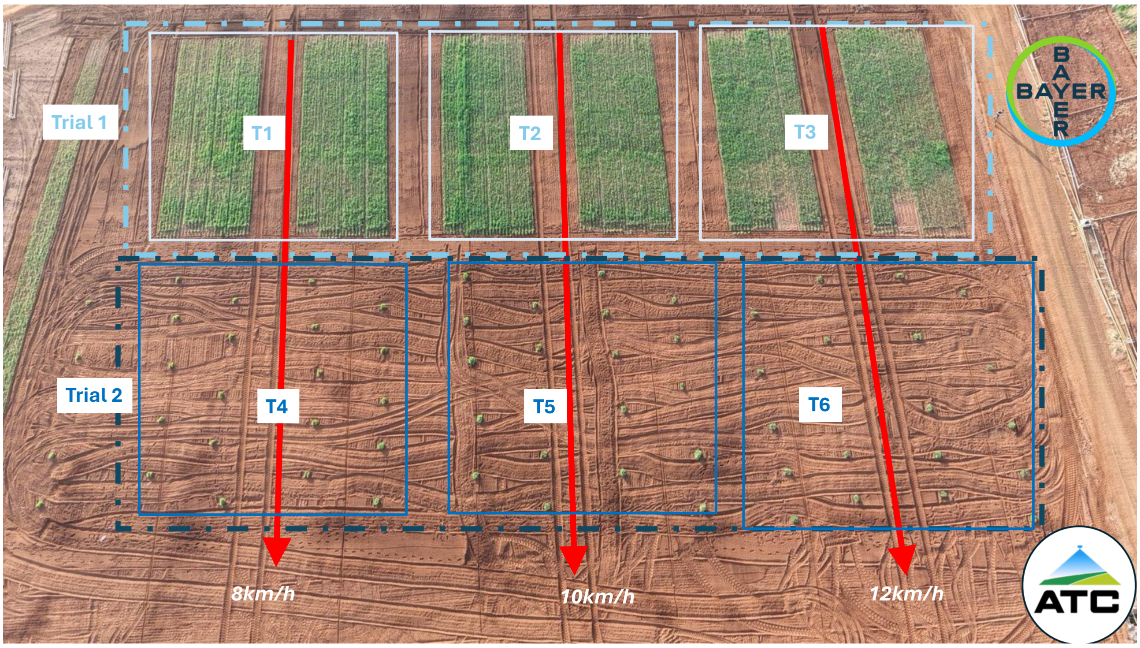
Two independent trials were conducted. The first trial focused on conventional total area application (broadcast), while the second trial evaluated targeted application based on camera systems. In both trials, applications were performed at three travel speeds: 8, 10, and 12 km h^{-1}, to analyze the effect of operational speed on the efficacy weed control. The plots designated for total area application (broadcast burndown of Brachiaria) totaled 500 m^2, comprising 4 repetitions per treatment. For the targeted application, the experimental area corresponded to 500 m^2, containing 10 targets of Brachiaria with approximately 0.50 m^2, distributed in a zig-zag pattern.

The spray applications were conducted using a self-propelled sprayer, maintaining a constant application rate of 200 L ha⁻¹ and a working pressure of 4.5 bar. The self-propelled sprayer used was the Jacto Uniport 2030, equipped with the retrofit SaveFarm targeted spraying system. The system featured a configuration of 25 cameras distributed approximately every 3 nozzles, with the nozzles spaced 0.35 m apart along the spray boom.

Before the installation of the trial, the spraying system was calibrated under 5% in comparison to nominal flow variation, using ISO 16122-2 (2024) sprayer inspection, from which the operational parameters were defined, including flow rate, boom high, pressure, PWM duty cycle, the relationship between treated area and travel speed, as well as maneuvering areas. These procedures aimed to ensure real and suitable operating conditions in the field, compatible with the commercial use of the equipment.

The system operated in targeted mode, activating the necessary nozzles for spraying based on weed detection. The system's response time was synchronized with the travel speed of the sprayer, ensuring the correct overlap between detection and application. The experimental design adopted was completely randomized, with three treatments and four repetitions for each trial, as follows: Trial 1: T1: broadcast at 8 km h⁻¹; T2: broadcast at 10 km h⁻¹; and T3: broadcast at 12 km h⁻¹. Trial 2: T4: spot spraying at 8 km h⁻¹; T5: spot spraying at 10 km h⁻¹; and T6: spot spraying at 12 km h⁻¹. The field design before application is in figure 1, where is possible to check the experiments and treatments.

Figure 1. Trial design before herbicide spray.



In this design it’s possible to understand the trial separation 1 and 2, the treatment areas as well the red lines what symbolize the machine direction and the speed test. Using this shape the sprayer could have a standard performance to better represent in comparison to farm scenario.

The application efficacy (weed control) was evaluated both qualitatively and quantitatively. The qualitative assessment was conducted by a specialist technician in weed management, considering the visual level plants control over time. The quantitative assessment was carried out using remote sensing, utilizing the Mavic 3 - Enterprise drone at a 80 meters flight altitude, with a resolution of 3.69 cm/pixel, and flights conducted at 7 and 14 Days After Application (DAA). From the aerial images, orthomosaics were generated on the DroneDeploy platform, and vegetation index maps (VARI - Visible Atmospherically Resistant Index) were calculated using QGIS software. VARI values were used as a quantitative indicator of the plants' response to herbicide, allowing inference of the level of plant stress and the efficacy of weed control over time.

The assessments conducted at 7 and 14 DAA, allowing for the monitoring of the herbicide's action dynamics and comparing the performance of the spraying systems at different operating speeds.

The ortomosaic processing was carried out using the VARI to analyze vegetation loaded into QGIS, where the necessary bands (red, green, and blue) were the VARI was calculated using the raster calculator, applying the appropriate formula (formula 1a) to generate a new raster layer. Next, the area of interest was delineated using a vector layer, and the raster clipping was performed using the clipping tool in QGIS, resulting in a raster layer that represents only the desired extent. These procedures ensured the acquisition of relevant data for the analysis of vegetation in the studied area.

Formula 1a. VARI math methods.

$$VARI = \frac{G - R}{G + R - B}$$

Following the introduction of the concept by Gitelson et al. (2002), the Visible Atmospherically Resistant Index (VARI) became widely known as the spectral index developed to estimate the greenness and density of vegetation, using only visible spectrum bands (green, red, and blue), offering greater resistance to atmospheric effects compared to other indices based on these same bands.

RESULTS AND DISCUSSIONS:

The qualitative assessment conducted at 7 and 14 DAA indicated (figure 2 and 3, and table 1) that there was no perceptible difference in the level of control of Brachiaria among the different travel speeds (8, 10, and 12 km h^{-1}), both in the trial with total area application and in the trial with targeted application. The results indicate that, under the operational conditions adopted (200 L ha^{-1} and 4.5 bar), the increase in travel speed within the studied range did not compromise the agronomic herbicide efficacy. This suggests that the quality of application was maintained even with variations in operational speed, possibly due to the stability of hydraulic parameters and an adequate spray rate that ensures good coverage and deposition. At all evaluated speeds, satisfactory control of the weed was observed, characterized by typical symptoms of glyphosate action. Cavalieri (2013) found similar results (deposition vs. travel speed) when using a standard flat fan nozzle, indicating that travel speed did not influence the deposition of the spray.

Figure 2. Regular drone image 7 Days After Application.

Figure 3. Regular drone image 14 Days After Application.

Table 1. Qualitative assessment results from the field trials 7 and 14 DAA.

Experiment	Treatment	7DAA	14DAA
Trial 1 (Broadcast)	T1	99,25%	100%
	T2	99,75%	100%
	T3	99,50%	100%
Trial 2 (Target)	T4	100%	100%
	T5	100%	100%
	T6	100%	100%

The quantitative analysis using the VARI (Visible Atmospherically Resistant Index) corroborated the results observed qualitatively. When comparing the VARI values between the two trials, a similar behavior was observed in the reduction of the spectral response associated with green vegetation, indicating that the level of control was equivalent between the conventional spraying system (broadcast) and the selective spraying system (spot), the figure 4 and 5 it's possible to observe the color range in the trials, and treatments.

Figure 4. VARI 7 Days After Application.

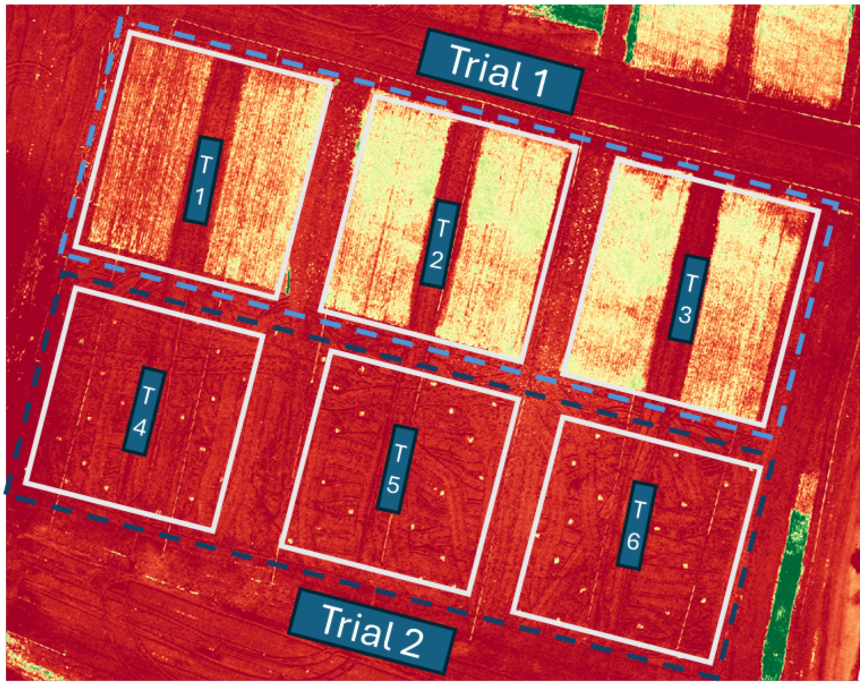
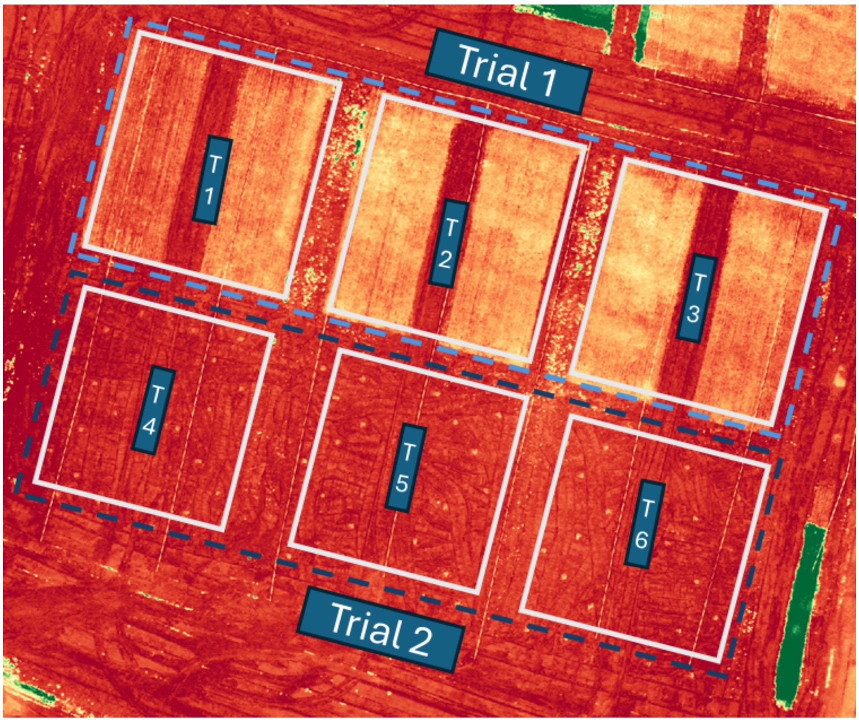


Figure 5. VARI 14 Days After Application.



The similarity in VARI patterns over time reinforces that both application methods were equally effective in controlling the target plant. These results demonstrate that selective spraying can achieve agronomic performance comparable to that of total area application, even under different operational speeds, representing a technically viable alternative for the rational management of weeds. Table 2 shows the digital results with the minimum and maximum values and the difference between both data.

Table 2. Quantitative assessment and digital results from field trials 7 and 14 DAA.

Experiments	Treatments	7 DAA			14 DAA		
		Min. Value	Max. Value	Difference	Min. Value	Max. Value	Difference
Trial 1 (Broadcast)	T1	-0,5294	-0,0303	0,4991	-0,3697	-0,0399	0,3299
	T1	-0,7797	0,0041	0,7838	-0,3519	0,0000	0,3519
	T1	-0,6316	0,0321	0,6636	-0,3185	-0,0266	0,2919
	T1	-0,6250	0,0205	0,6455	-0,3113	-0,0227	0,2887
	T2	-0,4464	0,0704	0,5169	-0,2800	-0,0628	0,2172
	T2	-0,4906	0,0417	0,5322	-0,2947	0,0132	0,3080
	T2	-0,4250	0,0841	0,5091	-0,2520	-0,0179	0,2342
	T2	-0,4384	0,0425	0,4808	-0,2593	0,0319	0,2911
	T3	-0,5000	0,0144	0,5144	-0,2542	-0,0109	0,2433
	T3	-0,3750	0,0699	0,4449	-0,2250	0,0407	0,2657
	T3	-0,5306	0,0263	0,5569	-0,3504	0,0066	0,3571
	T3	-0,5902	-0,0037	0,5865	-0,3866	-0,0128	0,3738
Trial 2 (Target)	T4	-0,2474	-0,0209	0,2265	-0,2887	-0,1004	0,1883
	T4	-0,2613	-0,0348	0,2265	-0,2941	-0,0930	0,2011
	T4	-0,2547	-0,0189	0,2358	-0,2950	-0,0889	0,2061
	T4	-0,1768	-0,0043	0,1725	-0,3008	-0,0886	0,2122
	T5	-0,1215	0,0079	0,1294	-0,2662	-0,0742	0,1920
	T5	-0,2404	-0,0138	0,2266	-0,3256	-0,0856	0,2400
	T5	-0,0722	0,0161	0,0882	-0,2958	-0,0772	0,2186
	T5	-0,2794	0,0161	0,2955	-0,2808	-0,0543	0,2265
	T6	-0,1412	0,0037	0,1449	-0,2574	-0,0612	0,1962
	T6	-0,1481	-0,0074	0,1408	-0,2946	0,0620	0,3566
	T6	-0,2444	0,0081	0,2525	-0,2774	-0,0333	0,2440
	T6	-0,2216	0,0039	0,2254	-0,2847	-0,0551	0,2296

The results indicate that in the qualitative assessment at 7 DAA there was no significant difference (ANOVA, $p = 0.49$) between treatments, while at 14 DAA all treatments had the same estimated efficacy.

In the quantitative assessment with VARI data (minimum values), the result shows a statistically significant difference for the broadcast application method at 7 DAA (Kruskal-Wallis, $p < 0.1$) and a statistically non-significant difference for spot application at 14 DAA (Kruskal-Wallis, $p = 0.12$) with a significance level of 5%. It was concluded that alternative efficacy quantification indices/methods that allow for equivalence with the qualitative assessment may be employed in the future.

CONCLUSION:

The established methodology for evaluating the effectiveness of herbicides broadcast applications compared to targeted spray was satisfactory, demonstrating good applicability when the correct parameters were used.

The traditional agronomic evaluation of product efficacy (qualitative) did not show significant differences between the systems in the treatments evaluated, between 7 and 14 DAA.

The evaluations of the VARI index (quantitative) showed statistically significant differences for the broadcast application method at 7 DAA, and statistically insignificant differences for the target application at 14 DAA.

In terms of innovation in spray science, further research is recommended to better understand the equivalence with traditional systems compared to new methods.

Digital evaluation, in relation to the visual method and reliable human experience performing the work, requires further investigation, as does the use of others digital index that can be as reliable as traditional pesticide performance evaluation.

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