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Scientific Article

Aerial application results in production gains in relation to ground application in soybean

Aplicação aérea resulta em ganho produtivo em relação a aplicação terrestre na soja

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ABSTRACT - Grain production plays a significant role in the economy and development of Brazil's agricultural sector, with a particular emphasis on soybeans. To achieve greater productivity and reduce production costs, the agricultural sector has adopted new technological alternatives, including Remotely Piloted Aircraft (RPA), also known as drones. The use of these aircraft for spraying is intended to provide practical and sustainable control of pathogens and weeds in crops. This study aims to compare terrestrial and aerial application methods to determine which operations provide productive gains in soybean cultivation. To achieve this goal, we monitored operations using Statistical Quality Control (SQC) tools and proximal remote sensing techniques. The experiment was conducted in the experimental areas of the Federal Technological University of Paraná (UTFPR), Campus Santa Helena, Paraná State. The experimental design was based on the basic premise of SQC, comprising 48 sample points for evaluating productivity and 16 sample points for other indicators in each application, totaling 96 points for productivity and 32 points for other indicators. The quality indicators included crop biophysical characteristics and vegetation indices. The statistical analyses included descriptive analyses and SQC tools. It was concluded that RPAs provided a more uniform application, and a significant increase in productivity was observed with aerial application compared to ground application.

Keywords: Precision agriculture. Statistical control of quality. *Glycine max* (L) Merril. Application technology.

RESUMO - A produção de grãos desempenha um papel significativo na economia e no desenvolvimento do setor agropecuário no Brasil, destacando-se, em particular, os grãos de soja. Com o objetivo de alcançar maior produtividade e redução nos custos de produção, observa-se que o setor agrícola tem adotado novas alternativas tecnológicas, incluindo o uso de aeronaves remotamente pilotadas (ARP) ou Remotely Piloted Aircraft (RPA), também conhecidas como drones. A utilização destas aeronaves para a pulverização visa o controle eficaz e sustentável de patógenos e plantas daninhas de cultivos agrícolas. Neste estudo, o objetivo foi comparar a aplicação terrestre e aérea para determinar qual dessas operações proporcionou ganhos produtivos na cultura da soja. Para isso, as operações foram monitoradas com base em ferramentas de Controle Estatístico de Qualidade (CEQ) e por meio do uso de sensoriamento remoto proximal. O experimento foi conduzido nas áreas experimentais da Universidade Tecnológica Federal do Paraná (UTFPR), *Campus* Santa Helena, Estado do Paraná. O delineamento experimental foi fundamentado nas premissas básicas do CEQ, compreendendo 48 pontos amostrais para a avaliação da produtividade e 16 pontos amostrais para os demais indicadores em cada aplicação, totalizando 96 pontos para produtividade e 32 pontos para os demais indicadores. Os indicadores de qualidade incluíram características biofísicas da cultura e índices de vegetação. As análises estatísticas realizadas abrangeram análises descritivas e ferramentas do CEQ. Concluiu-se que por meio dos RPAs, proporcionou-se uma aplicação mais uniforme, observou-se um aumento significativo da produtividade com a aplicação aérea em comparação com a aplicação terrestre.

Palavras-chave: Agricultura de precisão. Controle estatístico de qualidade. *Glycine max* (L) Merril. Tecnologia de aplicação.

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INTRODUCTION

Several challenges arise in grain production, including the control of diseases and pests during production cycles. Owing to its diverse climatic conditions, Brazil is subject to the emergence of diseases and pest attacks on crops. Among these diseases, those caused by fungi have emerged as one of the main phytosanitary problems in soybean crops, resulting in significant damage and loss. These factors reduce the quality and quantity of grains, resulting in a total loss of crop yield (SILVA et al., 2015).

Therefore, it is essential to implement improved crop management practices to avoid or minimize damage to production. Among these, the use of pesticides is particularly notable. Pesticides are considered one of the main strategies because of their effectiveness in controlling diseases, pests, and weeds (OLIVEIRA, 2016).

As part of its drive for increased grain yield and cost reduction, Brazilian agriculture has adopted new methods, including technologies integrated into (PA – Precision Agriculture). One such technology is the use of Remotely Piloted

Aircraft (RPA), which has proven to be a game changer in the sector. RPA enables a more efficient use of agricultural inputs, allowing for the precise management of treatments in cultivated areas. This approach helps prevent product waste, reduces environmental impacts, and ensures greater safety for producers (PACHECO, 2021).

The use of RPAs for spraying offers several advantages: there is no crushing of plants because applications are performed aerially; they outperform land-based agricultural machines, by accessing hard-to-reach areas; reduce contamination and environmental impact through the use of smaller volumes of solution and water; they lower costs by reducing the use of pesticides; and they increase agricultural yield, owing to the more efficient and precise application of pesticides to control diseases and pests (AMARAL et al., 2021).

Statistical Quality Control (SQC) was used to analyze the data collected and provide a more accurate assessment of the operational quality of the applications. SQC offers a statistical analysis that monitors the operational quality of mechanized agricultural systems, such as the applications conducted. With this control, it is possible to identify the operation in which there is more significant variability in the processes, thus increasing the crop yield (MONTGOMERY, 2016; SAMOHYL, 2009).

Thus, this study hypothesized that soybean yield could be increased using new application technologies, providing a more localized and sustainable application than terrestrial methods. The justification for this approach lies in that fact that current applications are predominantly terrestrial and often inefficient due to several factors, such as variable climatic conditions, air temperature and humidity, wind speed, and inadequate pesticide deposition. Therefore, this study aims to present promising results for aerial applications. This approach has the potential to positively affect the rational use of pesticides, culminating in the reduction of production costs and minimization of environmental impacts.

Considering the limited research in this area, this study aimed to compare the operational quality of RPA applications with that of traditional ground applications using boom sprayers. This study aimed to assess the effects of these methods on soybean crop yield.

MATERIAL AND METHODS

Study area description

The experiment was conducted in the experimental field at the Federal Technological University of Paraná (UTFPR), Santa Helena Campus, Paraná State, Brazil. The area has the following approximate coordinates: latitude –24º50’57” and longitude –54º20’44,” with an altitude of 237 meters above mean sea level. The region has a humid, subtropical climate. According to the Brazilian classification system, the experimental soil area is a Latossolic Distroferric Red Nitisol (SANTOS et al., 2018).

Experimental delineation

The experimental design was based on the basic premise of Statistical Quality Control (SQC). It comprised 48 sample points for evaluating the yield and 16 sample points for the other indicators in each application, totaling 96 points for the yield and 32 points for the other indicators. The treatments included aerial (RPA) and terrestrial (tractorized boom sprayer) application.

The area measured 160 m long and 30 m wide, totaling approximately 0.48 hectares for each treatment. A free space of 6 m was maintained between treatments to avoid drift and overlap between applications, resulting in a total experimental area of approximately 0.96 hectares. The spacing between the rows when sowing was 0.50 m, with a distribution of 12 soybean seeds m^{-1}.

Each sampling point was carefully chosen and located in a georeferenced quadrant with dimensions of 20 × 15 m. Comprehensive evaluations of quality indicators were conducted, including plant height, canopy length, yield, and proximal sensing, through vegetation NDVI and NDRE.

Plants were collected from three central lines of five meters per treatment to evaluate the yield indicator, with three repetitions of measurements per sampling point. The average of three lines for this indicator was calculated for each sample point. For plant height and canopy length, three plants were randomly chosen from each quadrant per sampling point. After collection, the data were averaged for each sample point. For the NDVI and NDRE indicators, measurements were measured at five meters for each sampling point using the RapidScan® CS-45 active optical sensor.

Agricultural machinery and equipment

Soybeans were sown in a direct planting area on October 25, 2022, using the cultivar M6110 I2X (6301 I2X). The area was fertilized with the NPK 1-20-20 formulation at the recommended dose of 280 kg ha^{-1}. The university's agricultural machinery and equipment, renowned for their reliability, were used in the experiment. The LS Plus 90 model tractor, valued for its performance and 90 hp engine, was coupled with a PDN 7000 model mechanical seeder, which had seven rows spaced 0.50 m apart.

For the ground applications, a terrestrial sprayer coupled to the Jacto brand tractor was used, featuring a capacity of 600 L, 12 meter-wide bars, nozzles spaced every 0.5 meters, and TeeJet brand tips, model 11002. For aerial applications, aircraft models T10 and T30 were used with a TXA 80015 tip and an application range width of 5 and 7 m, respectively. The settings used in the experiment established the parameters for comparing application modalities (terrestrial and aerial), as listed in Table 1.

Three applications were carried out during the soybean cycle as part of the experimental management, as shown in Table 2. The first experiment took place on November 28, 2022, and consisted of desiccating bitter grass in the area. Two additional applications followed: the second, on December 15, included herbicide, fungicide, and insecticide products; and the third, on January 16, 2023, involved the application of fungicides only.

Additionally, during the application process, we closely monitored the environmental conditions and ensured that they remained consistent throughout both ground and aerial applications. The recorded average conditions were as follows: a temperature of 27 °C, relative humidity of 79%, and a wind speed of 2.2 km h^{-1}.

Table 1. Operating parameters used for ground and aerial applications.

Operating parameters	Application method		
	Terrestrial – Tractorized sprayer	Aerial - RPA T10 model	Aerial - RPA T30 model
Spray Tank (L)	600.00	10.00	30.00
Volume of syrup (L ha^{-1})	120.00	13.50	13.00
Speed (km h^{-1})	8.00	22.00	20.00
Application height (m)	0.50	2.50	3.00

RPA: Remotely Piloted Aircraft.

Table 2. Applications carried out during the experiment.

Date	Commercial product name	Active ingredient	Dosage (0.48 ha)
November 28, 2022	Cletodim/Select	Cletodim	0.48 L
December 12, 2022	Zapp; Mancozeb; Elatus; Bold.	Glifosato; mancozebe; azoxistrobina, benzovindiflupir; acetamiprido and fenpropatrina.	0.72 L; 0.72 kg; 0.072kg;
January 1, 2023	Mancozeb; Elatus	Mancozebe, azoxistrobina and benzovindiflupir	0.72 kg; 0.072 kg;

Quality indicators

The quality indicators included biophysical crop characteristics such as plant height, canopy length, and yield, as well as the Normalized Difference Vegetation Index (NDVI) and normalized difference red-edge index (NDRE) vegetation indices. The date of the most significant yield indicator was carefully chosen. Below is a detailed description of how the measurements were taken on four different dates (Date 1 – December 9, 2022; Date 2 – January 11, 2023; Date 3 – February 16, 2023; and Date 4 – March 1, 2023), with only one date considered as the yield indicator (harvest day, days 5 – 17, 2023).

Plant height: The height of the soybean crop was measured from the soil surface to the maximum leaf height. The assessment was performed manually using graduated measuring rods and decimal metrics.

Canopy length: Measurements were obtained from one end of the canopy to the other. This measurement was performed manually using graduated tape and a decimal metric system.

Vegetation indices: NDVI and NDRE were obtained using the RapidSCAN® CS-45 active optical sensor positioned 0.60 m above the canopy. The calculations of these indices are presented in Table 3.

Yield: Samples were collected manually from a 5 m² area and taken to the laboratory to measure grain moisture. The value was corrected to 13% water content, and the weight of each sample was assessed on a digital scale and then extrapolated to kg ha^{-1}.

Statistical analyses

The statistical analyses included descriptive statistics and CEQ tools, which involved control charts of individual values using Minitab® software. We also used analysis of variance (ANOVA) to assess the effects of different treatments on soybean yield. Following significant results, we applied Tukey's test for further comparison. Statistical analyses were performed using AgroEstat® software. Additionally, we used QGIS® software, version 3.22.10, to generate the maps.

The control charts for individual values consisted of the arithmetic mean of the sample and the upper control limits (UCL), according to Equation 1, and the lower control limits (LCL), according to Equation 2. The calculations of these limits are shown in the following equations (TOLEDO et al., 2008).

$$\text{UCL} = \text{average} + 3 \text{ times standard deviation} \tag{1}$$
$$\text{LCL} = \text{average} - 3 \text{ times standard deviation} \tag{2}$$

RESULTS E DISCUSSION

Descriptive analysis

Using the results of the descriptive analysis (Tables 3 and 4), we observed the behavior and variations in the biophysical characteristics of the soybean crop according to the collection of data on different dates, from which we concluded that the variation in these characteristics could interfere with crop yield. This analysis included mean values; average standard error; standard deviation (SD); coefficient of variation (CV); minimum, median, and maximum; Ryan-Joiner (RJ) normality test; and p-values. The Ryan-Joiner normality test was used to verify the data normality. When the P-value of the RJ test was > 10%, the data were considered normally distributed.

Table 3. Plant height, canopy length, NDVI (Normalized Difference Vegetation Index), NDRE (Normalized Difference Red Edge Index), and yield are evaluated according to the seasons for terrestrial application.

Seasons evaluated*	Aver.	SE Aver.	SD	CV	Min	Med	Max	RJ	P-value
				Plant height (m)					
Date 1	0.44	0.01	0.03	7.54	0.40	0.43	0.51	0.97^{N}	>0.10
Date 2	0.65	0.02	0.09	13.45	0.36	0.67	0.76	0.83^{NN}	<0.01
Date 3	0.76	0.01	0.06	7.28	0.63	0.77	0.83	0.98^{N}	>0.10
Date 4	0.76	0.02	0.06	7.86	0.62	0.76	0.84	0.97^{N}	>0.10
				Plant canopy length (m)					
Date 1	0.37	0.06	0.25	67.83	0.27	0.32	1.32	0.60^{NN}	<0.01
Date 2	0.36	0.01	0.04	9.90	0.29	0.36	0.43	0.99^{N}	>0.10
Date 3	0.57	0.15	0.59	103.38	0.32	0.43	2.77	0.56^{NN}	<0.01
Date 4	0.32	0.01	0.04	12.80	0.24	0.32	0.39	1.00^{N}	>0.10
				NDVI					
Date 1	0.64	0.01	0.05	8.18	0.56	0.63	0.75	0.98^{N}	>0.10
Date 2	0.64	0.01	0.04	6.61	0.56	0.64	0.70	0.98^{N}	>0.10
Date 3	0.71	0.02	0.07	9.28	0.55	0.72	0.78	0.94^{NN}	0.05
Date 4	0.62	0.01	0.03	5.52	0.58	0.61	0.68	0.96^{N}	>0.10
				NDRE					
Date 1	0.22	0.01	0.03	11.66	0.19	0.22	0.27	0.97^{N}	>0.10
Date 2	0.23	0.00	0.01	6.25	0.20	0.23	0.26	0.99^{N}	>0.10
Date 3	0.27	0.01	0.03	10.26	0.20	0.27	0.30	0.97^{N}	>0.10
Date 4	0.21	0.00	0.02	7.50	0.19	0.21	0.25	0.93^{NN}	0.03
				Yield (kg ha^{-1})					
Date 5	1332.30		55.60	385.20	28.91	710.10	1204.50	0.95^{NN}	<0.01

*Date 1 (December 9, 2022), Date 2 (January 11, 2023), Date 3 (February 16, 2023), Date 4 (March 1, 2023), and Date 5 (March 17, 2023 – Harvest date).
Aver. - Average, SE Mean - standard error of the mean, SD - standard deviation, CV - coefficient of variation, min - minimum, max - maximum, RJ - Ryan-Joiner normality test, N - Normal distribution of the data according to the RJ test, NN - Non-normal distribution of the data according to the RJ test.

In the descriptive analysis, Tables 3 and 4 show that on Date 1 of height assessment, the average plant height was 0.44 m for both treatments. A variation was observed in the second assessment, where the ground application resulted in a plant height five centimeters higher than that of the aerial application. When we analyzed the data for Date 3, we observed an inversion of this variable between the treatments. On this date, ground application obtained an average of 0.76 m, while aerial application recorded 0.73 m. In the evaluation for Date 4, the average height for ground application remained stable at 0.76 m, while the average height for aerial application was 0.75 m.

When we analyzed the plant canopy length, we found that many data points did not meet the normality assumptions of the RJ test. Therefore, we evaluated the canopy width medians. The median canopy width of the RPA applications was greater than that in the ground application treatments. Thus, there was a difference in this quality indicator between the treatments, ranging from one to three centimeters between treatments. On Date 1, aerial application had a greater canopy width (0.39 m) seven centimeters greater than the median for the ground application, which was 0.32 m wide.

These data are usually used as NDVI quality indicators, especially for aerial applications, rather than ground applications. When analyzing the averages, it can be seen that, on Date 1, the average for ground application was 0.64 m, while for aerial application, it was 0.63 m. On Date 2, ground and aerial application averages were 0.64 m and 0.69 m, respectively. On Date 3, the averages were 0.71 m for ground application and 0.74 m for aerial application, representing an increase for both the NDVI variables. However, on Date 4, the average for NDVI was 0.54 m for aerial application, while for ground application, it was 0.62 m.

The decline in NDVI values observed during the fourth evaluation date is linked to reduced chloroplast density and photosynthetic activity as the plants enter the senescence phase (TAIZ et al., 2021). At this stage, a decrease in chlorophyll content changes leaf pigmentation, leading to reduced reflectance in the near-infrared region and, consequently, lower NDVI values (FORMAGGIO et al., 2017). This trend was expected because sensors typically detect higher NDVI readings in greener plants with higher chlorophyll concentrations. As senescence advances, leaf coloration becomes more saturated and depigmented, decreasing the spectral response of the vegetation indices. Similar patterns were noted by Farias et al. (2023), who found that the NDVI values tended to decline at the beginning of soybean maturation because of leaf yellowing and abscission, indicating index saturation under senescent conditions.

The NDRE data showed average values of 0.22 for the ground application and 0.23 for the aerial application on Date 1. On Date 2, the averages were 0.23 m and 0.26 m, respectively. On Date 3, the measurements were 0.27 m for the ground application and 0.28 m for the aerial. On Date 4, the value was reduced, with 0.21 m for the terrestrial and 0.19 m for the aerial application.

Table 4. Plant height, canopy length, NDVI (Normalized Difference Vegetation Index), NDRE (Normalized Difference Red Edge Index), and yield are evaluated according to the seasons for aerial application.

Seasons evaluated*	Aver.	SE Aver.	SD	CV	Min	Med	Max	RJ	P-value
				Plant height (m)					
Date 1	0.44	0.01	0.03	5.73	0.38	0.44	0.48	0.97^{N}	>0.10
Date 2	0.60	0.02	0.07	10.79	0.47	0.61	0.71	0.97^{N}	>0.10
Date 3	0.73	0.01	0.05	6.56	0.64	0.73	0.82	0.98^{N}	>0.10
Date 4	0.75	0.01	0.05	6.95	0.66	0.76	0.87	0.97^{N}	>0.10
				Plant canopy length (m)					
Date 1	0.46	0.08	0.34	73.63	0.32	0.39	1.73	0.57^{NN}	<0.01
Date 2	0.37	0.01	0.05	13.74	0.31	0.37	0.47	0.98^{N}	>0.10
Date 3	0.59	0.15	0.60	101.79	0.38	0.44	2.85	0.54^{NN}	<0.01
Date 4	0.36	0.02	0.07	19.14	0.28	0.35	0.58	0.90^{NN}	<0.01
				NDVI					
Date 1	0.63	0.01	0.04	6.86	0.57	0.62	0.72	0.98^{N}	>0.10
Date 2	0.69	0.01	0.04	6.17	0.62	0.67	0.76	0.97^{N}	>0.10
Date 3	0.74	0.01	0.03	4.65	0.67	0.75	0.78	0.96^{N}	>0.10
Date 4	0.54	0.01	0.05	9.47	0.43	0.55	0.64	0.98^{N}	>0.10
				NDRE					
Date 1	0.23	0.00	0.02	6.71	0.21	0.23	0.26	0.98^{N}	>0.10
Date 2	0.26	0.00	0.02	6.19	0.23	0.25	0.29	0.98^{N}	>0.10
Date 3	0.28	0.00	0.02	5.84	0.26	0.27	0.31	0.98^{N}	>0.10
Date 4	0.19	0.01	0.02	10.61	0.16	0.19	0.23	0.98^{N}	>0.10
				Yield (kg ha^{-1})					
Date 5	1711.00		50.90	352.50	20.60	967.80	1739.80	0.99^{N}	>0.10

*Date 1 (December 9, 2022), Date 2 (January 11, 2023), Date 3 (February 16, 2023), Date 4 (March 1, 2023), and Date 5 (March 17, 2023 – Harvest date).
SE Mean - standard error of the mean, SD - standard deviation, CV - coefficient of variation, min - minimum, max - maximum, RJ - Ryan-Joiner normality test, N - Normal distribution of the data according to the RJ test, NN - Non-normal distribution of the data according to the RJ test.

The final evaluation was conducted on Date 5, focusing on the final yield for each treatment. We observed that aerial application yielded better results than ground application, with an average of 1,711 kg ha^{-1} in the treatment using RPAs and 1,332.30 kg ha^{-1} using a ground sprayer. Using RPAs, we obtained results of 378.70 kg ha^{-1} higher than that of ground spraying.

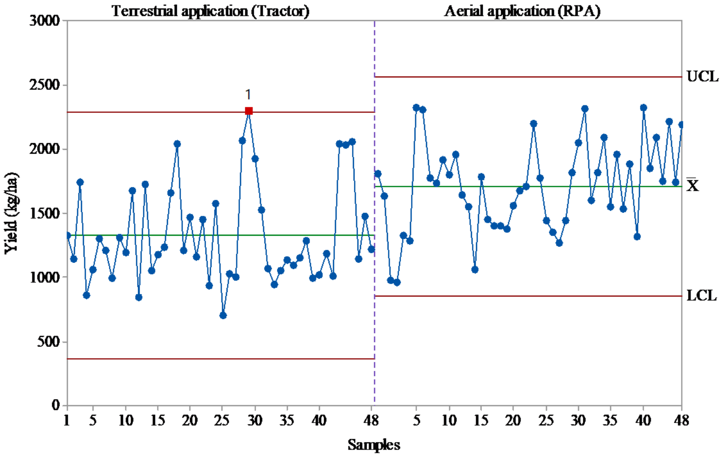
The quality indicator data from aerial applications demonstrated lower dispersion than ground applications, which suggests a decrease in operational variability; this observation aligns with findings reported by Reis et al. (2010). Such results are further supported by normality tests and measures of central tendency and dispersion (see Table 4).

Individual value control charts

Control charts, along with individual value control charts, play a crucial role in our analysis. They provided a clear visual representation of the behavior of the data, allowing us to understand the variability in the data related to the biophysical evaluation of soybean crops and vegetation indices. These charts also help us assess the quality of operation of the equipment used. The distributions of the points, variations, and limits present in the control charts, including the upper (LSC) and lower (LIC) control limits located at the ends of the figure, are all key indicators. The behavior of the data was analyzed using points and their proximity or distance to the central line, indicated by the green color, which represents the general average of the variable. When these points exceed the control limits (LSC and LIC), they are attributed to special factors that impact the operational quality and increase data variability (SAMOHYL, 2009).

Notably, in the control chart of individual yield values (Figure 1), a higher process quality was observed for aerial applications (REIS et al., 2010). Moreover, the process average was higher than that for ground application, underscoring the potential of this approach to significantly boost yield, primarily because of the reduction in plant crushing.

At sample point 30, the yield variability was well beyond the average, indicating some interference in this sample. However, in the aerial application, it is possible to observe a higher average yield and greater control in the data, where the points are closer to the average yield, and no points are highlighted in the chart. This suggests that there was no variability or interference in the yield data in the aerial application treatment, either in the management operation or climatic factors. These results corroborate the observations in Table 4 through descriptive analysis.

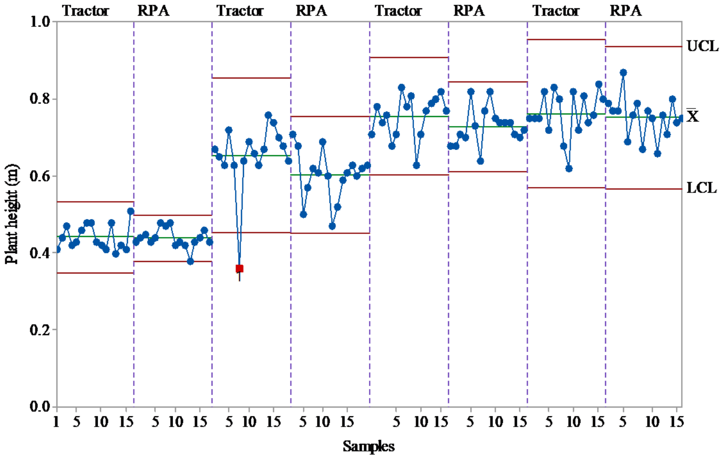


LSC - Upper Control Limit, LIC - Lower Control Limit, and $\bar{x}$: Average

Figure 1. Control chart of individual values for the quality indicator yield (kg ha^{-1}) as a function of terrestrial application (tractor-mounted boom sprayer) and aerial application (RPA - Remotely Piloted Aircraft).

The results obtained from the control charts for the plant height indicator (Figure 2) showed that in the evaluations carried out according to the dates, the process behavior was very similar for ground and aerial applications on Date 1. However, the distribution of points between the limits in the ground application showed greater variability than in the aerial application, where the data were very close to the average, ensuring greater uniformity in the height of the plants in the stand.

These observations are crucial for understanding the consistency and stability of operations and provide valuable insights for crop management, particularly regarding the uniformity of plant growth and development. This is especially relevant in terrestrial applications because uneven plant heights can result in variations in the height of the application boom.



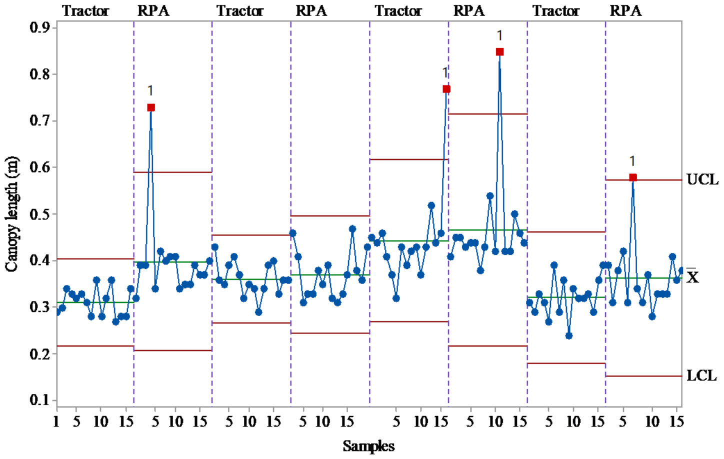
LSC - Upper Control Limit, LIC - Lower Control Limit, and $\bar{x}$: Average

Figure 2. Control chart of individual values for plant height (m) as a function of terrestrial application (tractor-mounted boom sprayer) and aerial application (RPA - Remotely Piloted Aircraft).

Plant development was better on Date 2 (Figure 2) than on Date 1. Growth was greater in the ground application than with aerial application, although one point was below the lower control limit, as shown. The out-of-control point in this treatment was identified as the occurrence of special interference, which may also be related to the rapid and uneven growth of the stand.

The data from Dates 3 and 4 (Figure 2) showed a stable process with no special causes, points distributed between the boundary lines, and no points outside the extremities. This provides data with less variability and no risk of special causes interfering with the charts. However, the points in the aerial application were closer to the average during both evaluations, indicating better uniformity in the stand compared to the treatment carried out with ground application. These analyses were essential for assessing the consistency of plant growth and identifying possible external influences on the results.

The control chart for the canopy length indicator (Figure 3) showed greater variability in the data for both treatments, and there was no point above the LSC on Date 2. On Date 1, the average canopy length for aerial applications was greater than that for ground applications. However, one out-of-control point was identified, indicating that Sample Point 5 was interfered with, causing variability in the data and instability in the process for that date.



LSC - Upper Control Limit, LIC - Lower Control Limit, and $\bar{x}$: Average

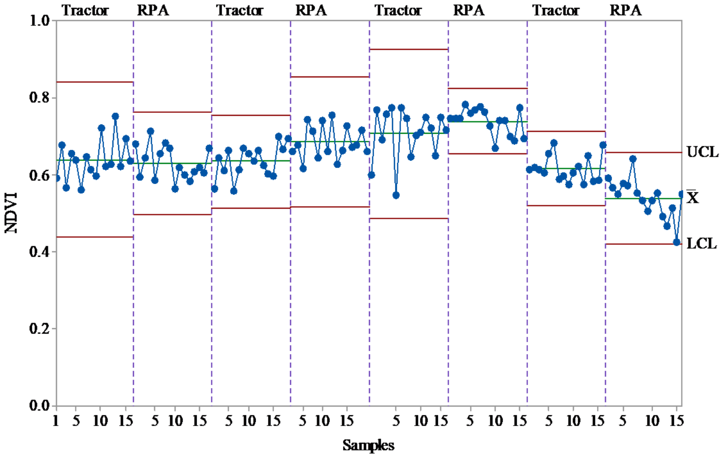
Figure 3. Control chart of individual values for plant canopy length (m) as a function of terrestrial application (tractor-mounted boom sprayer) and aerial application (RPA - Remotely Piloted Aircraft).

On Date 2, the points were distributed within the control limits, indicating a stable performance with only random variations inherent to the process. Unlike special causes, which represent failures or issues encountered during operations, these random causes do not negatively affect the quality of the process. Furthermore, the average canopy length from this evaluation was similar across treatments in the experiment.

The evaluation on Date 3 revealed that both treatments exhibited variability at one sampling point in each plot, suggesting the influence of random causes on the process.

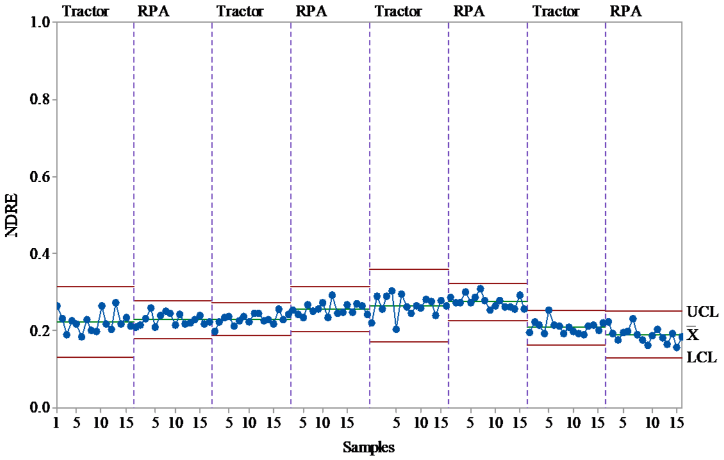
On Date 4, the length of the plant canopy in both the ground and aerial applications decreased. This reduction can be partly attributed to the assessment conducted when the plants enter their natural senescence, a stage that leads to a decrease in biomass. The data collected during this evaluation revealed that the control chart showed the dispersion of a point in the aerial treatment, indicating variability at this sample point due to an external factor.

Quality control was confirmed in the control charts of the individual values of NDVI (Figure 4) and NDRE (Figure 5). No points fell outside the control limits across the four evaluation dates. When analyzing the average, dispersion can be seen among the data points, which explains the diversification of the vegetation indices.



LSC - Upper Control Limit, LIC - Lower Control Limit, and $\bar{x}$: Average

Figure 4. Control chart of individual values for NDVI (Normalized Difference Vegetation Index) as a function of terrestrial application (tractor-mounted boom sprayer) and aerial application (RPA - Remotely Piloted Aircraft).



LSC - Upper Control Limit, LIC - Lower Control Limit, and $\bar{x}$: Average

Figure 5. Control chart of individual values for NDRE (Normalized Difference Red Edge Index) as a function of terrestrial application (tractor-mounted boom sprayer) and aerial application (RPA - Remotely Piloted Aircraft).

Throughout all evaluation periods, the NDVI and NDRE displayed consistent values with less variability across all assessment dates in the cycle. This consistency contributes to the quality control of the operations. Both treatments showed data points that were very close to the averages, ensuring uniformity, particularly for the NDRE data. This uniformity is not affected by external factors. The lower susceptibility of NDRE to saturation compared to NDVI likely accounts for this behavior, as noted by Carneiro et al. (2020) and Carneiro et al. (2022).

Comparison between terrestrial and aerial applications

Analysis of variance (ANOVA) of grain mass data collected at harvest revealed significant disparities among treatments. Subsequently, Tukey's test was conducted, which revealed noteworthy differences between the applications. In particular, aerial applications demonstrated superior yield results compared with ground applications. This finding has practical implications, as illustrated in Figure 6, where the yield of the aerial application treatment was 6.3 bags ha^{-1}, and one soybean bag corresponded to 60 kg, surpassing that of the ground application treatment.

The observed increase in yield with the application of RPAs can be attributed to their effective performance. As Silva Neto et al. (2021) discussed, RPAs conduct targeted applications in specific locations, leading to the improved control of diseases, pests, and weeds. This finding is supported by Andrade et al. (2018), who noted the effectiveness of aerial applications in controlling weeds, even when conducted at a height of 15 m above the crop.

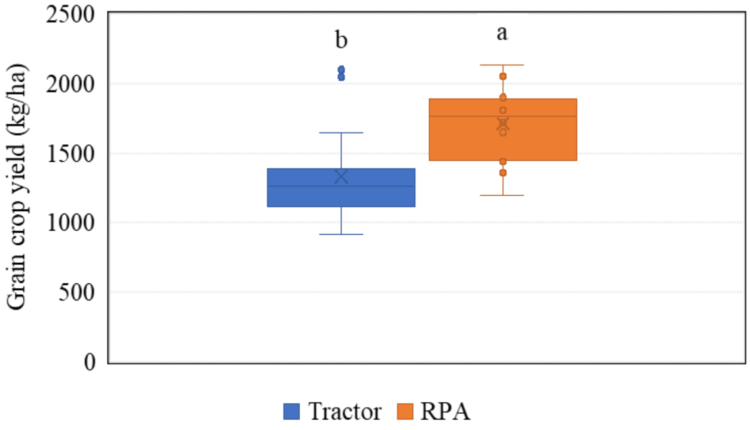


Figure 6. Comparison of means using Tukey's test according to RPA and tractor applications. Different letters represent significance according to Tukey's test (p-value < 5%).

In contrast, terrestrial applications often damage plants because of trampling and soil compaction, particularly in areas without controlled traffic-farming systems. These issues can adversely affect crop development and productivity (JUSTINO et al., 2006). Aerial applications avoid direct contact between the plants and the soil surface, thereby minimizing mechanical damage and structural degradation. This reinforces the potential of aerial applications as sustainable and less invasive alternatives.

CONCLUSION

Aerial applications using RPA have shown superior operational consistency, improved biophysical indicators, and increased productivity compared with traditional ground application methods. The higher values of NDVI, NDRE, plant height, and canopy length observed in the RPA treatments indicated better vegetative growth and a more vigorous plant structure. Additionally, the average yield obtained through aerial application was 378.7 kg ha^{-1}, or approximately 6.31 bags ha^{-1}, which was higher than that obtained from ground application. These findings underscore their effectiveness.

Thus, aerial application of RPAs is a technically advanced alternative that can enhance soybean crop yields, reduce operational variability, and allow for more efficient use of agricultural inputs. Furthermore, RPAs are a viable, efficient, and sustainable option for ground spraying, leading to increased soybean productivity and a more rational use of inputs. These findings emphasize the importance of incorporating digital technologies into precision agriculture, which can optimize phytosanitary management and foster both economic and environmental benefits in the production system.

REFERENCES

ANDRADE, J. M. de A. et al. Avaliação de RPAs para pulverização em diferentes culturas. **Ingeniería y Región**, 20: 72-77, 2018.

AMARAL, L. R. et al. Aplicações de drones na agricultura. In: QUEIROZ D. M et al. (Org.). **Agricultura digital.** 2. ed. atual. e ampl. São Paulo, SP: Oficina de Texto, 2021. 223 p.

CARNEIRO, F. M. et al. Biophysical characteristics of soybean estimated by remote sensing associated with artificial intelligence. **Bioscience Journal**, 38: 1-12, 2022.

CARNEIRO, F. M. et al. Comparison between vegetation indices for detecting spatial and temporal variabilities in soybean crop using canopy sensors. **Precision Agriculture**, 21: 979-1007, 2020.

FARIAS, G. D. et al. Normalized Difference Vegetation Index (NDVI) for soybean biomass and nutrient uptake estimation in response to production systems and fertilization strategies. **Frontiers in Sustainable Food Systems**, 3: 1-12, 2023.

FORMAGGIO, A. R. et al. **Sensoriamento remoto em agricultura**. São Paulo, SP: Oficina de Textos, 2017. 288 p.

JUSTINO, A. et al. Sentido de pulverização em culturas de soja e feijão com pulverizador de barras. **Engenharia Agrícola**, 26: 755-758, 2006.

MONTGOMERY, D. C. **Introdução ao controle estatístico da qualidade**. 7. ed. Rio de Janeiro, RJ: LTC, 2016. 549 p.

PACHECO, A. L. **Agricultura 4.0: Um levantamento das tecnologias para o futuro da agricultura**. Monografia (Graduação em Agronomia) - Universidade Federal de Mato Grosso do Sul, Chapadão do Sul, 2021.

OLIVEIRA, L. F. Sanidade de grãos de milho em função de material genético ou fungicidas foliares. Monografia (Graduação em Agronomia) - Universidade Federal de Mato Grosso, Instituto de Ciências Agrárias e Ambientais, Sinop, 2016.

REIS, E. F. et al. Liquid aerial pesticide application quality with an experimental agricultural aircraft in soybean crop *(Glycine Max L.).* **Engenharia Agrícola**, 30: 958-966, 2010.

SAMOHYL, R. W. **Controle estatístico de qualidade**. 1 ed. Rio de Janeiro, RJ: Elsevier, 2009. 352 p.

SANTOS, H. G. et al. **Sistema Brasileiro de Classificação de Solos**. 5. ed., rev. e ampl. Brasília, DF: Embrapa, 2018. 356 p.

SILVA, D. D. et al. **Micotoxinas em cadeias produtivas do milho: riscos à saúde animal e humana**. Sete Lagoas, MG: Embrapa Milho e Sorgo, 2015. 27 p. (Documentos, 193).

SILVA NETO, J. O. et al. Aeronave Remotamente Pilotada (RPA) para aplicação de agrotóxico. **Research, Society and Development**, 10: 1-9, 2021.

TAIZ, L. et al. **Fundamentos de Fisiologia Vegetal**. 6. ed. Porto Alegre, RS: Artmed, 2021. 584 p.

TOLEDO, A. et al. Caracterização das perdas e distribuição de cobertura vegetal em colheita mecanizada de soja. **Engenharia Agrícola,** 28: 710-719, 2008.