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Quality of coffee planting techniques by aerial sensors and statistical process control[1]

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ABSTRACT - Planting is considered one of the most essential steps in coffee growing. Lack of uniformity in planting may compromise future operations. Therefore, verifying planting operations quality is fundamental to optimizing production processes and reducing costs. This study aimed to investigate planting techniques through Statistical Process Control (SPC) and aerial images. Carried out in two areas, managed manually and semi-mechanized in the Bom Jardim Farm (MG – Brazil). Data were collected through Remotely Piloted Aircraft (RPA). Quality control charts and density maps were used to identify variations in distribution and spacing between plants and planting rows. It was found that the planting carried out manually was 4.7% wider than projected due to spacing reduction from 0.5 m to 0.48 m. The semi-mechanized system displayed a deficit of 7% compared to the projected planting system, using 0.55 m between plants. The density map showed the most significant planting alignment variations. Despite displaying lower results than the manual system, the semi-mechanized system improvements are valid for their minimal average variations. Thus, correcting points found outside the limits can increase the efficiency of semi-mechanized planting.

Key words: Remote sensing. Process Quality. Precision Agriculture.

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INTRODUCTION

Coffee growing is considered one of the principal agricultural activities in the world (SUJARITPONG; YOO-KONG; BHADOLA, 2021). Given this importance, some management changes are observed. Coffee growing is known to occupy elevated manual work, but the current production field can be fully mechanized (FERNANDES *et al.*, 2012). Planting coffee by a semi-mechanized or mechanized system has become a viable alternative for producers because it increases operational capacity and reduces costs (PELOIA; MILAN, 2010).

Managing coffee plantations can contribute to production process improvements. Identifying irregularities in planting makes it possible to perform changes in future operations. Performance information, operational quality, and machines' working capacity are essential in mechanized systems management, aiding decision-making (VIDAL *et al.*, 2016).

Applications of technologies used in industry have the potential use in agriculture to increase productivity and quality of management. Statistical Process Control (SPC) has been systematically explored; in industry, this methodology is necessary to measure and control the production quality process (HRVAČIĆ, 2018). From the collection of continuous data, this technology allows the identification of regions with the potential to reduce productivity, providing effective diagnoses in the prevention and detection of problems in the assessed processes (ILBEIGI, 2019).

Some studies demonstrate the SPC effectiveness in improving agricultural processes, which were verified in quality studies in mechanized herbicide application in wheat (SUGUISAWA *et al.*, 2007), vegetation cover distribution and losses in mechanized soybean harvest (TOLEDo *et al.*, 2008), mechanized harvesting in irrigated coffee planting (CUSTÓDIO *et al.*, 2012), sprinkler irrigation quality (ANDRADE *et al.*, 2017), and damage and loss diagnosis in mechanized tomato harvesting (SOARES *et al.*, 2019).

Continuous data collection is required to generate SPC charts. Thus, data collected by remotely piloted aircraft (RPA) can be inserted into the process. An RPA's feature is the high capacity for agricultural monitoring (CHEMURA; MUTANGA; DUBE, 2017). Considered a precision agricultural technology, RPA quickly collects data in high spatial resolutions (PUTRA *et al.*, 2020), assisting in crop management decision-making and increasing efficiency and productivity (OLIVEIRA *et al.*, 2018).

Mechanization is a significant advance in agriculture. Studies have shown a cost reduction due to mechanical operation inclusion in sugar cane planting (Afonso *et al.*, 2018), forage planting (ANDRADE *et al.*, 2016), and mechanized tomato harvesting (CUNHA *et al.*, 2014). Mechanized planting is a fundamental function of the vegetable production process. Mechanization can reduce work intensity, improve production efficiency, and ensure planting quality (LI *et al.*, 2015). Nonetheless, besides providing operational work capacity and cost reduction, it must supply equal or higher quality than manual farming (ROCHA; TSUJIMOTO; MENEZES SOBRINHO, 1991).

Factors such as manual work replacement, management interference in following operations, and high investment employed in planting periods require studies of the efficiency of coffee planting techniques. Thus, knowledge of coffee planting quality can improve field production and reduce operational costs.

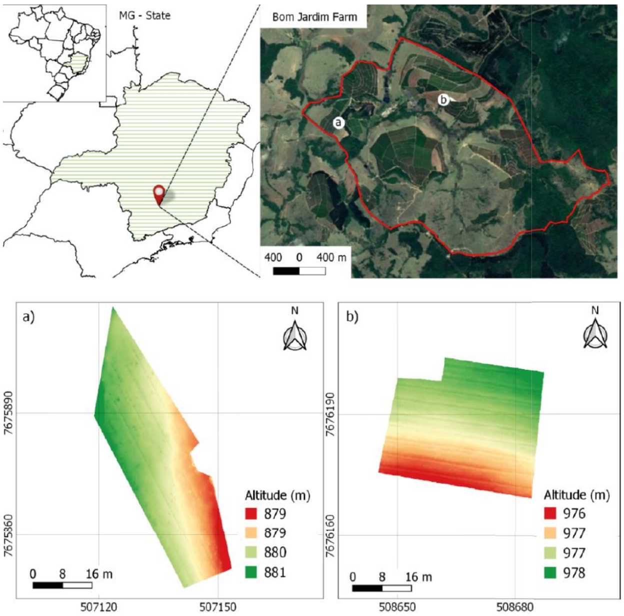
Due to the reduced research range regarding coffee planting quality and planting process improvement, this study aimed to investigate the alignment, distribution, and quality of manual and semi-mechanized planting using remotely piloted aircraft, statistical process control, and density maps.

MATERIALS AND METHODS

Study site

This study was performed in two experimental areas of 0.1 ha^{-1} (Figure 1) located in Bom Sucesso - Brazil, at the coordinates 21°00'55.55" S e 44°54'57.75" W. The region is characterized by a warm and temperate climate, with average annual temperatures ranging from 20 to 22 °C, rainfall around 1300 - 1600 mm, and an altitude of 800 - 1000 meters (ALVARES *et al.*, 2013).

Figure 1 - Experiment area location and digital elevation models: a) manual planting and b) semi-mechanized planting. Bom Jardim Farm, municipality Bom Sucesso - MG



Planting

This study assessed two planting operations: a manual and a semi-mechanized system (Figure 2). The experiments were started with the planting furrows already prepared and then planted with the coffee variety Catuai Red IAC 99, grown in sachets and distributed into the desirable spacing of 3.5 m between rows and 0.5 m between plants.

Regarding manual planting, eight workers participated in seedling box transport and lying them in defined locations. The defined planting used a 50 m string with markings every 0.5 m to obtain the spacing between planting rows and plants. Finally, the planting furrows were opened with a Chilean shovel (Figure 2a).

The semi-mechanized experiment used a semi-mechanized transplanting platform for 12 seedling boxes. (Figure 2b). The machine performed furrow openings in this system, and the seedlings were laid based on odometer rotation. Later, furrow closing and compaction were carried out manually.

Two auxiliary workers were needed to insert seedlings in the transplanting system, one worker to supply the boxes in the platform and the tractor operator. The traction source was Massey Ferguson MF 4275 compact 4 x 2 tractor with Front Auxiliary Traction (FAT), 55.0 kW (75 hp) engine power, used at 1500 rpm, 2R gear operating and 1.75 km h^{-1} average theoretical displacement.

Data collection and processing

The information concerning the planting methods was obtained through image capture using Remotely Piloted Aircraft (RPA). DJI Phantom 4 Advance model, GPS / GLONASS Positioning System equipped with a CMOS sensor, 1-inch capture photos up to 20 megapixels.

Flight planning started with area recognition to determine flight plan settings, which defined the landing and take-off point, called home. Climatic conditions, such as cloud amounts, sunlight levels, and wind speed, were checked, besides the presence of birds in the area before the flight.

The flights started at noon due to few clouds and little sun interference. Thus, flight plan characteristics were the following: 30 m height, 03 m.s-^{1} speed, and 80% lateral and longitudinal overlap, obtaining resolution spatial of 1.68 cm in three spectral bands - Red, Blue, and Green (RGB). Regarding image processing, we used the Agisoft PhotoScan 1.4 software, and for the mosaic formation and RGB bands union, we utilized the processing parameters described in Table 1.

Concerning the plant distribution analysis, the transplanted seedling quantity was counted for each planting system, with information extracted from the orthomosaic. Thus, the planted distribution percentage compared to the projected one was defined. Projected planted quantity refers to the 0.5 m spacing between plants and 3.5 m between lines.

Spacing analyses between plants and planting rows were performed using statistical process control (SPC). The charts identify non-randomness caused by some external factor and evaluate operations quality. This approach presents an essential criterion for data visualization, so the points plotted within calculated limits can be considered process-acceptable. The control charts also present complementary criteria for quality analysis, including occurrence point sequence, upward-downward trends, cyclical patterns shift, and points plotted close to control limits and grouped around the mainline (SZEKUT *et al.*, 2018).

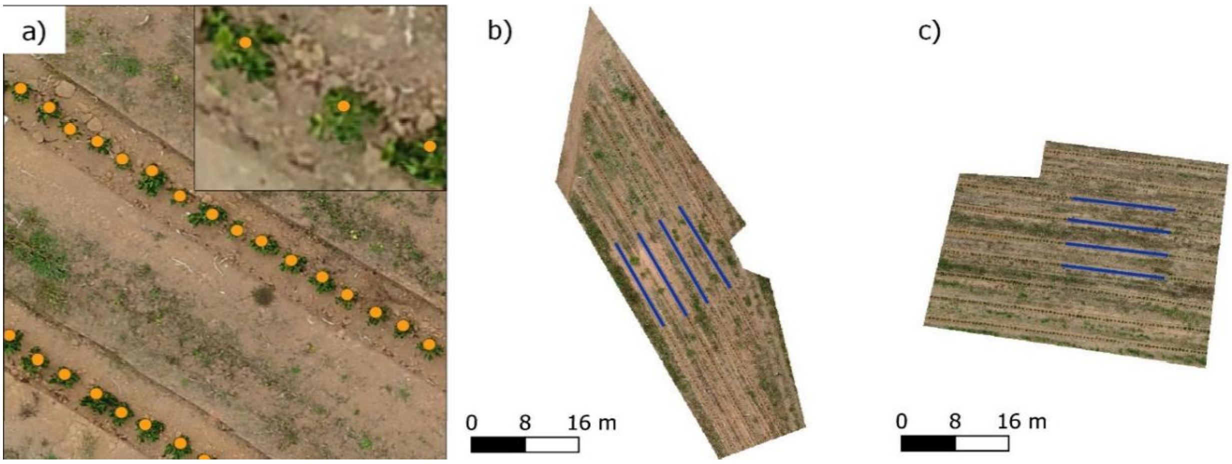
Figure 2 - Planting operations: a) semi-mechanized and b) manual planting of *Coffea arabica* L. seedlings, Bom Jardim Farm

Table 1 - Workflow carried out at Agisoft PhotoScan, for orthomosaics formation

Parameters	Settings
Align Photos	Highest
Accuracy	
Build Dense Cloud	Medium
Quality	
Depth filtering	Aggressive
Build Mesh	Arbitrary
Surface Type	
Build ORTHOMOSAIC	Mosaic
Mode Combination	
Surface	Mesh

Variables analyzed in each planting system were plant distribution, the spacing between plants, and spacing between planting rows. Figure 3 shows the data collection plan from visualizing high-image resolution using QuantumGis 3.1 software. The plants were manually marked using a points layer (Figure 3a). Then, a shapefile was generated with all planted area information, such as desired spacing (between planting rows and between plants), plant number, and failure percentage

Figure 3 - Identification of plants through seedlings visualization in RGB image: a) lines of sample collections for generating the Statistical Process Control (SPC) charts, b) manual planting, and c) semi-mechanized planting



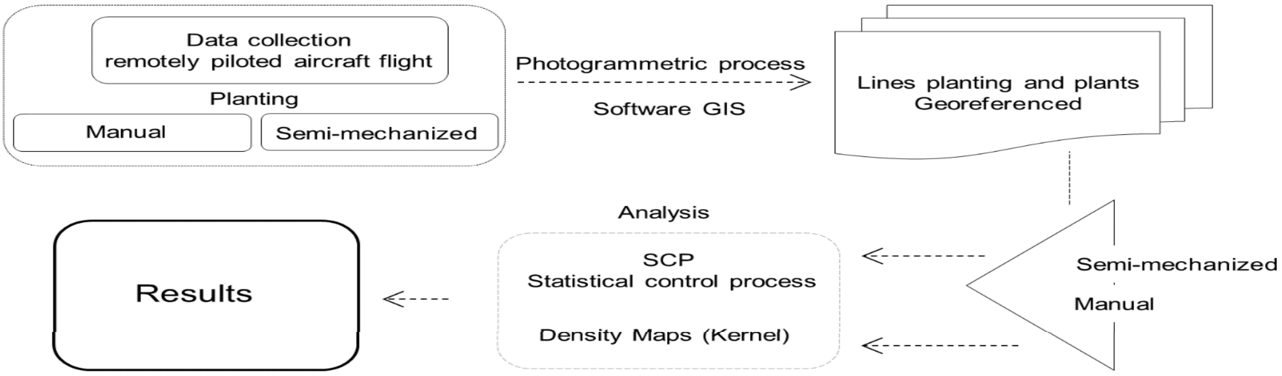
Numeric data for distance analyses between plants and between planting rows were obtained using manual measurements in ArcGIS 10.2 software. Planting row start and cultivation border data were eliminated from the statistical treatment. Each observation consists of 16 meters each (3b manual and 3c semi-mechanized Figure). For data extraction from the spacing between plants, four repetitions were performed at 16-meter planting. Regarding spacing analysis between planting rows, three repetitions were performed in 16 meters of planting.

Statistical 7 software was used to generate statistical process control graphs of X BAR S type, in which it is presented in two ways: one considering samples collected averages and the other about the samples' standard deviation, known as a reach graph and plotted by control charts with three lines: central line, indicating observed values average, lower control limit (LCL) and upper control limit (UCL). Quality graphics generation was a methodology described by Molnau *et al.* (2001), presented in equations 1,2 and 3.

$$\overline{X} = \mu \tag{1}$$

$$UCL = \mu + 3\frac{\sigma}{C_2\sqrt{n}} \tag{2}$$

Figure 4 - Workflow process methodology



$$LCL = \mu - 3\frac{\sigma}{C_2\sqrt{n}} \quad (3)$$

Where;

$\overline{X}$: Central line;

μ: Subgroups average;

UCL: Upper control limit;

LCL: Lower control limit;

σ: Standard deviation;

c2: Adjustment common distribution factor, tabulated according to n;

n - sample size.

Density maps were generated with points obtained by high-resolution images complementary to the confidence of geospatial information (Figure 3a). Maps displaying the actual situation of manual and semi-mechanized planting density were also created. A projected planting density map simulating a coffee planting with an ideal spacing of 0.5 x 3.5 m over the study area was prepared to compare the experiments and the study area projected.

A density map represents the original nonlinear data patterns conversion into a linearly separated format using kernel functions (XU *et al*., 2012). A kernel function is a K function (x I, x j) used to explain a nonlinear decision limit applied to susceptibility maps (VAPNIK, 1995). A quadratic kernel is a particular case polynomial with degree d = 2 used for nonlinear problem classification (SHASTRY, SANJAY, DEEXITH, 2017). Density values were obtained using Equation 4.

$$K(X,Y) = \left(X^{T}Y + C\right)^{2} \quad (4)$$

Where

X and Y: internal products;

C: Optional constant;

T: transposition factor.

The methodology used in this work involves several data collection and processing steps. Therefore, the processes performed to obtain the results are presented as a flowchart (Figure 4).

This flowchart contributes to a better visualization of the results presented, showing the steps for extracting the results.

RESULTS AND DISCUSSION

Plant distribution

The results in Table 2 show variations in plant numbers distributed in each system. Manual planting distributed 21 plants more than projected. This occurrence can happen due to string variation (Stretching) of the planting markers since its total length is 50 m.

Table 2 shows that a few centimeters could happen due to operational efficiency planting interference. Manual planting proved more efficient regarding plant distribution since it added 4.7% to the field planting.

Reducing spacing between plants on the row, even outside the desirable range, can bring benefits. Ronchi *et al.* (2015) show that reducing plant spacing up to 0.41 m causes increases in the root dry matter, length, volume, and surface area by soil volume without compromising the root-specific-length surface or root system deepening.

Table 2 - Plant amount in planting systems and spacing (meters) between plants of data extracted by photogrammetry. Δx: amount variation in seedlings between projected and transplanted

	Semi-mechanized	Manual
Projected seedlings (x_1)	629	441
Planted Seedlings (x_2)	585	462
Δx	-44	21
Error (%)	7.00	4.70
Spacing between plants (m)		
Mean	0.55	0.48
Minimal	0.31	0.21
Maximum	1.11	0.93

Considering that spacing reduction shows considerable productivity increase, Silveira *et al.* (2018) reinforce that factors such as cultivar choice and spacing between planting rows and between plants in planting rows most contribute to increased productive potential.

When analyzing Table 2, it was observed that manual planting performed better. This system presented an average distribution of 0.48 m between plants (projected 0.5 m), which resulted in 21 transplanted plants above the projected amount. Research by Andrade *et al.* (2014), when evaluating spacing combinations between rows and plants on rows, observed that spacing reduction between rows can increase productivity.

Spacing reduction between plants over the years can bring difficulties in coffee planting assertiveness. Research by Matiello *et al.* (2010) evidenced a concern with plant row spacing in coffee fields in the last 30 years. They presented trends for spacing reductions between plants in the line, with variations between 0.5 and 1 m. This reduction in planting density is faced with difficulty by semi-mechanized processes for perennial crops since the operation consists of already germinated plants deposited in plastic bags.

Semi-mechanized planting distributed 7% less than projected (Table 2). In semi-mechanized operations, planting speed can contribute to reduced performance. Manually powered planting platform operations may cause errors due to a lack of synchronization between man and machine. Lack of system feeding during coffee plantation can occur due to plant shortage, platform vibration, worker error, planting speed, and skidding traction machine.

Replanting need (transfer) is evidence of low-quality planting. In semi-mechanized planting platforms, an essential factor is the planting speed since the human capacity to follow rate seedling deposition in transplanting systems must be considered (ALMEIDA, 2019). Researching tomato transplant quality, Machado *et al.* (2015) concluded that semi-mechanized tomato transplantation with lower speed resulted in more excellent uniformity in the distribution of plants, leading to fewer replanting work demands.

Spacing between plants

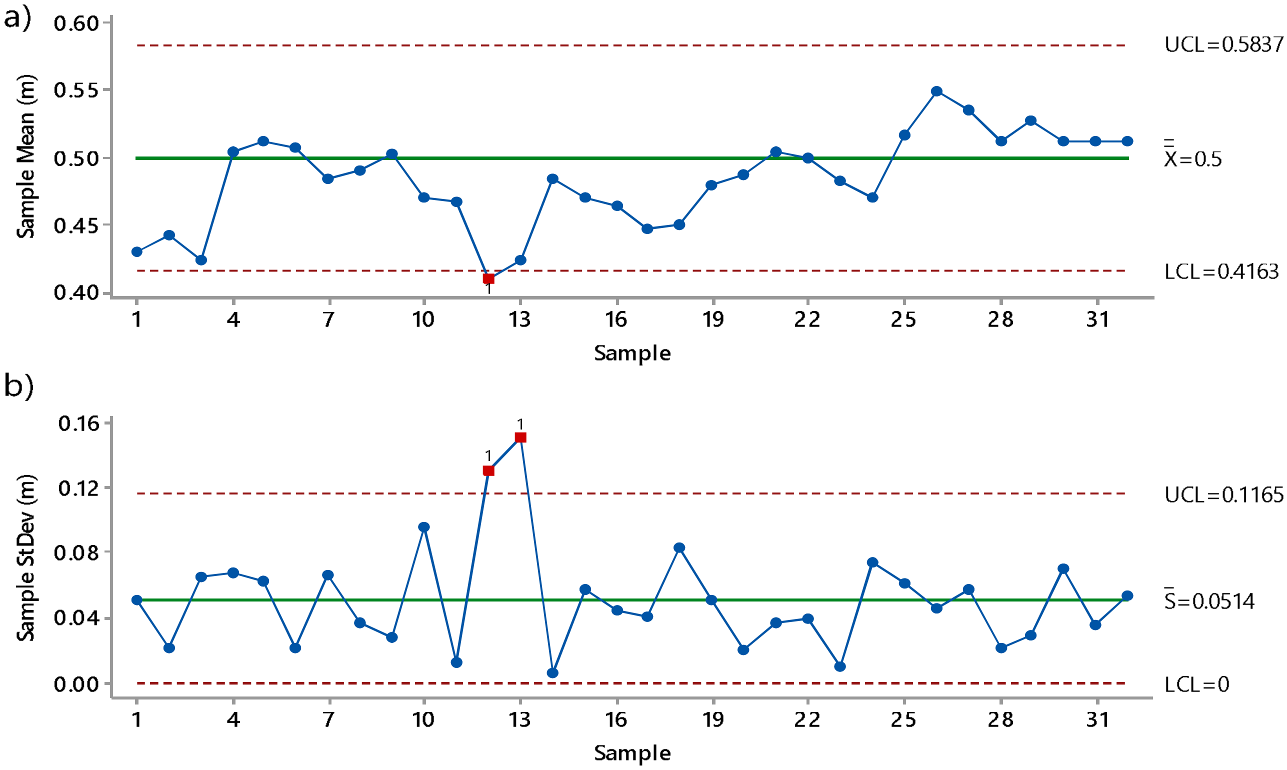
Transplanting manual system data are presented in Figure 5 (control charts). Note that point 12 exceeds the limits calculated in the control chart mean (Figure 5a). This variation may have occurred due to failures in planting, densification, worker errors, or some physical barrier.

The manual planting system showed excess variations in the range chart upper limits, observed in points 12 and 13, highlighted in red in Figure 5b, where it is also possible to visualize a high standard deviation variation between 0 and 0.11 m.

Monitoring productive processes in (SPC) can have two variation causes: common and special ones. Therefore, when it contains only common variations causes, the variables follow a normal distribution, in this case, within the calculated limits. The special ones are caused by significant reasons and altered process parameters, mean and standard deviation, presenting points outside the defined limits (MARTINS; LAUGENI, 2005). However, it is also essential to consider variations around the average amplitude. Abrupt variations around the average without exceeding calculated limits are to be regarded as intrinsic operational variations.

Errors from special causes are shown in Figure 5, displaying, for example, sample 12 recorded below the lower limit, a phenomenon occurring due to planting density since most points are below the projected average (0.5 m). Figure 5b also displays high data variation around the average. This variation is inherent to manual processes since each worker behaves differently, and this is influenced by causes such as planting experience, age, and physical characteristics, among others.

Figure 5 - Graphs of Statistical Process Control (SPC) for coffee planting (manual system). Y-axis: distance variations between plants in the line in meters. X-axis: sampling points, a) Averages of observations, and b) standard deviation of samples. UCL: Upper control limit and LCL: Lower control limit



Control charts (Figure 5b) presented variations above the upper control limit. There is a discrepancy between the means at points 12 and 13, which occurred due to increased distance between plants at these points, indicating that the planting row is not uniformly distributed.

Results shown in figure 5b can assist in future operations. These representations can allow one to identify distant points from the average. Therefore, when conducting a plantation plan, it is possible to identify the errors in vulnerable regions and recommend corrections to the following planting operations.

Errors from special causes in agricultural operations can occur due to several factors, such as incorrect equipment adjustment, operator experience, soil conditions differences, travel speed variations, and pest attacks, to cite a few (CHIODEROLI *et al*., 2012). Thus, control charts in semi-mechanized systems can identify non-transplanted points, improve crop formation, and assist in transplant system adaptations.

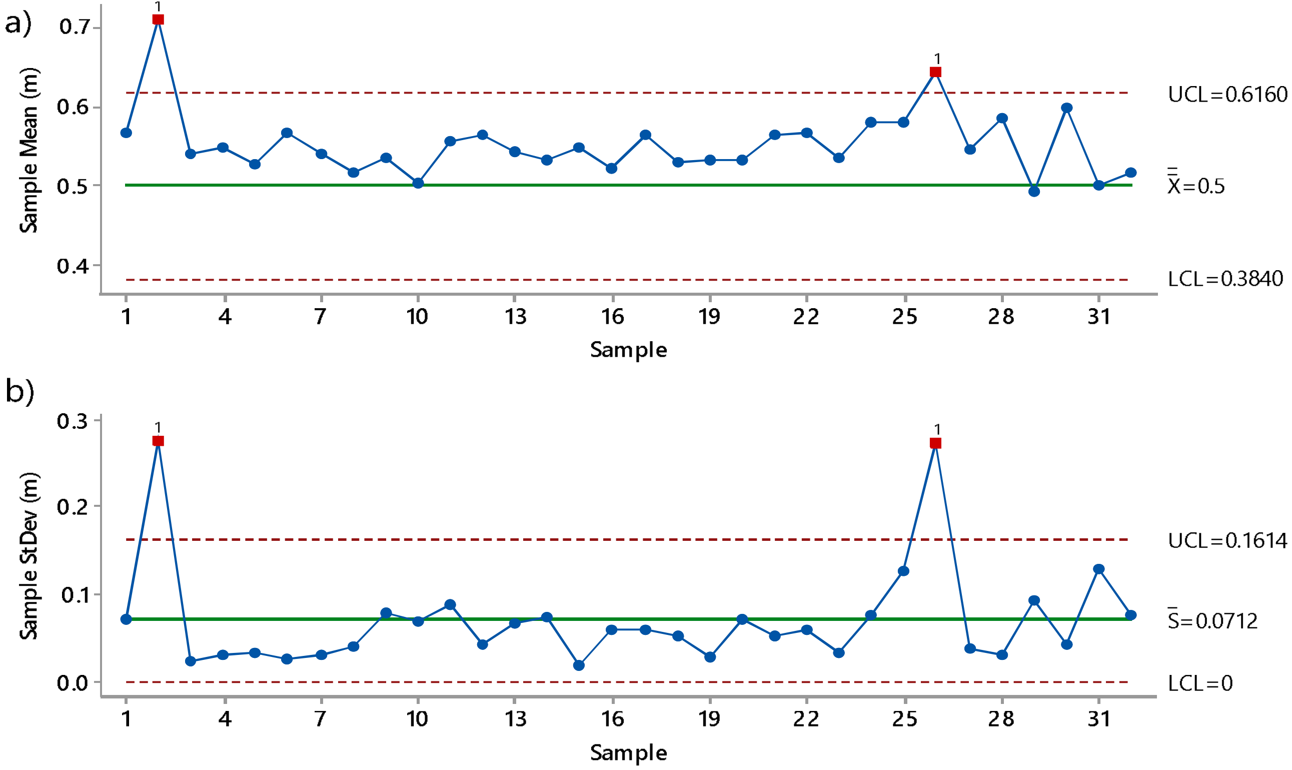
Visualization of errors made in the semi-mechanized planting operation is shown in Figure 6. In the control chart Figure 6a, the data are characterized all above the projected mean spacing (0.5 m) but follow a normal distribution. Variations in the range graphs (Figure 6b) demonstrate that semi-mechanized planting distributes plants more evenly.

Figure 6 shows semi-mechanized system results. It can be observed in Figures 6a and 6b, two variation peaks in points 2 and 26, outside the upper control limit. Because there are two planting failure samples, they denote plants' absence between these points due to the 1.11-meter spacing between plants.

Although there are planting failures, as presented in control charts (Figure 6a), plant distributions in the mechanized system were better than in manual ones, with fewer average variations. Points identified outside of control limits are linked to special causes variations, with the possibility that identified factors cause process instability (NORONHA *et al*., 2011; ZERBATO *et al*., 2014).

Data presented in Figure 5b show high spacing values between plants, with the highest pacing variations occurring between point 2 (0.31-0.57 m) and point 26 (0.69-0.44 m), respectively. It can be justified, by Table 1 information, that these variations happened due to low plant stand, average spacing values of 0.55 m, and planting failures.

Figure 6 - Graphs of Statistical Process Control (SPC) for coffee planting (system semi-mechanized). Y-axis: variations of distances between plants in the line in meters, X-axis: sampling points, a) Averages of observations, and b) standard deviation of samples. UCL: Upper control limit and LCL: Lower control limit



Planting platform efficiency depends on a continuous workable system. So, failures occurred due to operation uniformity lack. Cunha *et al.* (2018) reported the efficient operation of planting coffee semi-mechanized systems can vary due to support team interference. Mechanization improvement by SPC charts was found in peanut crops. Zerbato *et al.* (2017) show that field operations' continuous monitoring allows possible sowing failure detection. Thereat, future operations can be corrected and maintained within acceptable quality standards.

Spacing between planting lines

Manual planting performance can be observed in Figure 7. Some points have exceeded this system's lower and upper control limits (Figure 7a).

Errors in manual operations were observed and corrected by visual identification at operation time and can be linked to workers' numbers. Values presented in Figure 7b show manual operation having a high variation around average, caused by workers' large number since each worker has a planting manner. Data presented in Figure 8 detailed semi-mechanized planting; this figure shows spacing between planting rows, making it possible to observe a lack of planting uniformity.

It is possible to observe, in Figure 8, the semi-mechanized system instability. This system instability follows a continuous error model because one planting line error can interfere with others in mechanized operation. Possibly, the operator tried to correct the planting operation during a subsequent row but ended up carrying out the idea beyond.

Results presented by Silva *et al.* (2014) show that points outside control chart limits in coffee plantation alignment can be linked to possible sudden changes in direction by an operator during operation.

A possibility to reduce such errors would be by using the light bar or autopilot equipment. Research by Baio and Moratelli (2011) showed that autopilot use allows a more significant line number per area since it presents greater accuracy about the planting system than manual piloting. Therefore, this factor should not be considered exclusive for correct planting. Voltarelli *et al.* (2013) report that instabilities were found in sugar cane planting in lands on a 6% slope when conducting autopilot system operation.

Figure 7 - Graphs of Statistical Process Control (SPC) for coffee planting (manual system). Y-axis: variations of distances between lines of planting in meters, X-axis: sampling points, a) Averages of observations, and b) Standard deviation of samples. UCL: Upper control limit and LCL: Lower control limit

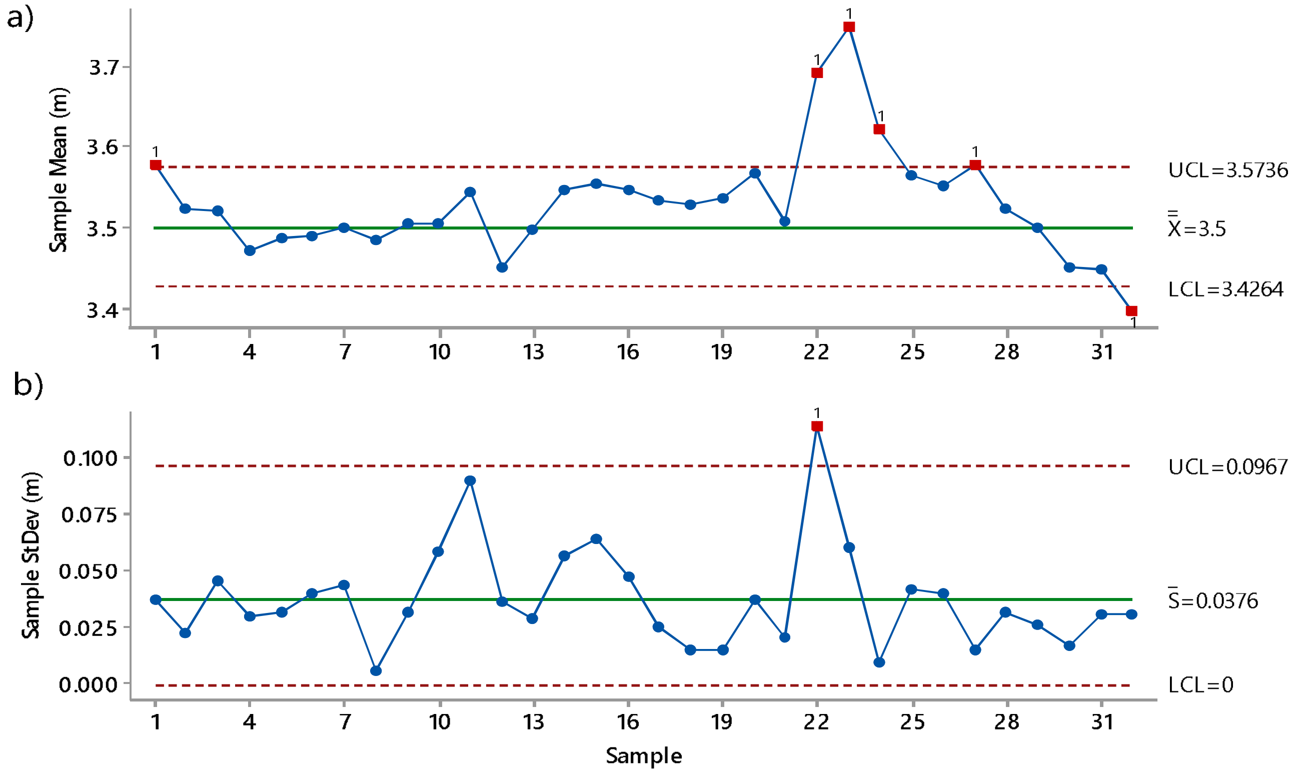
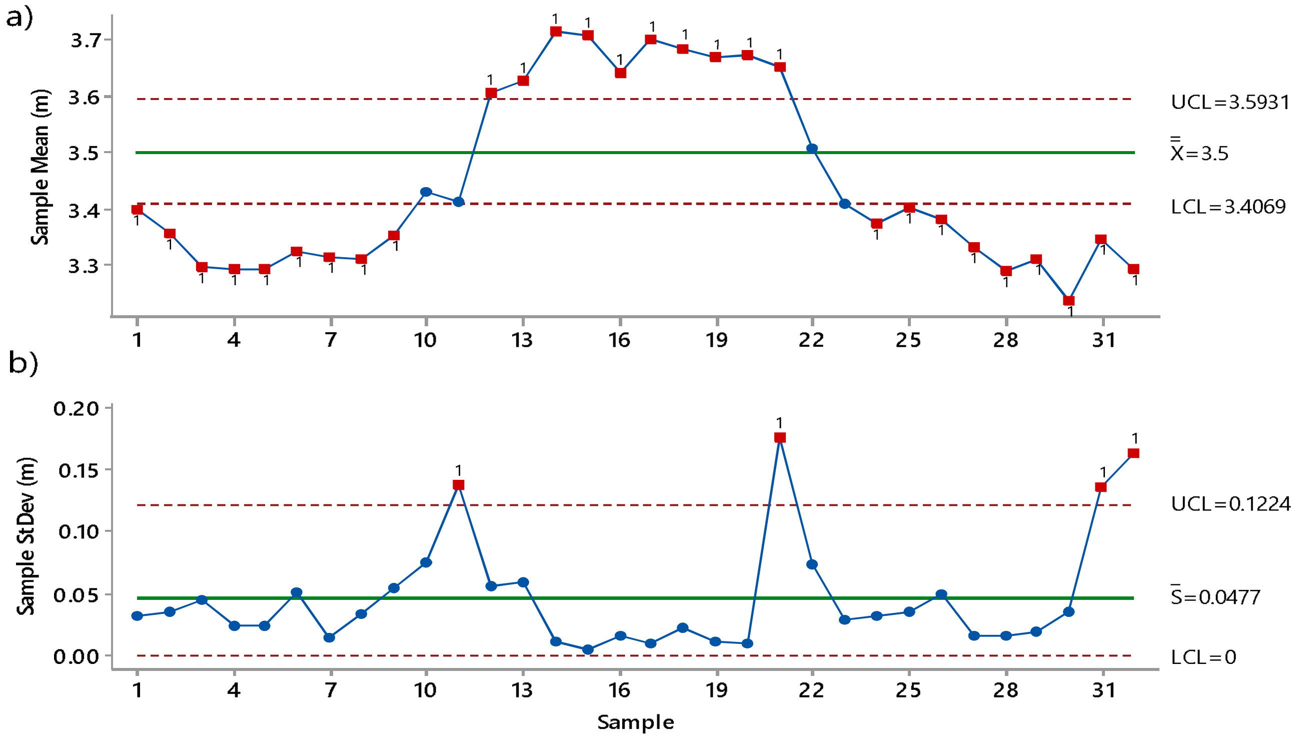


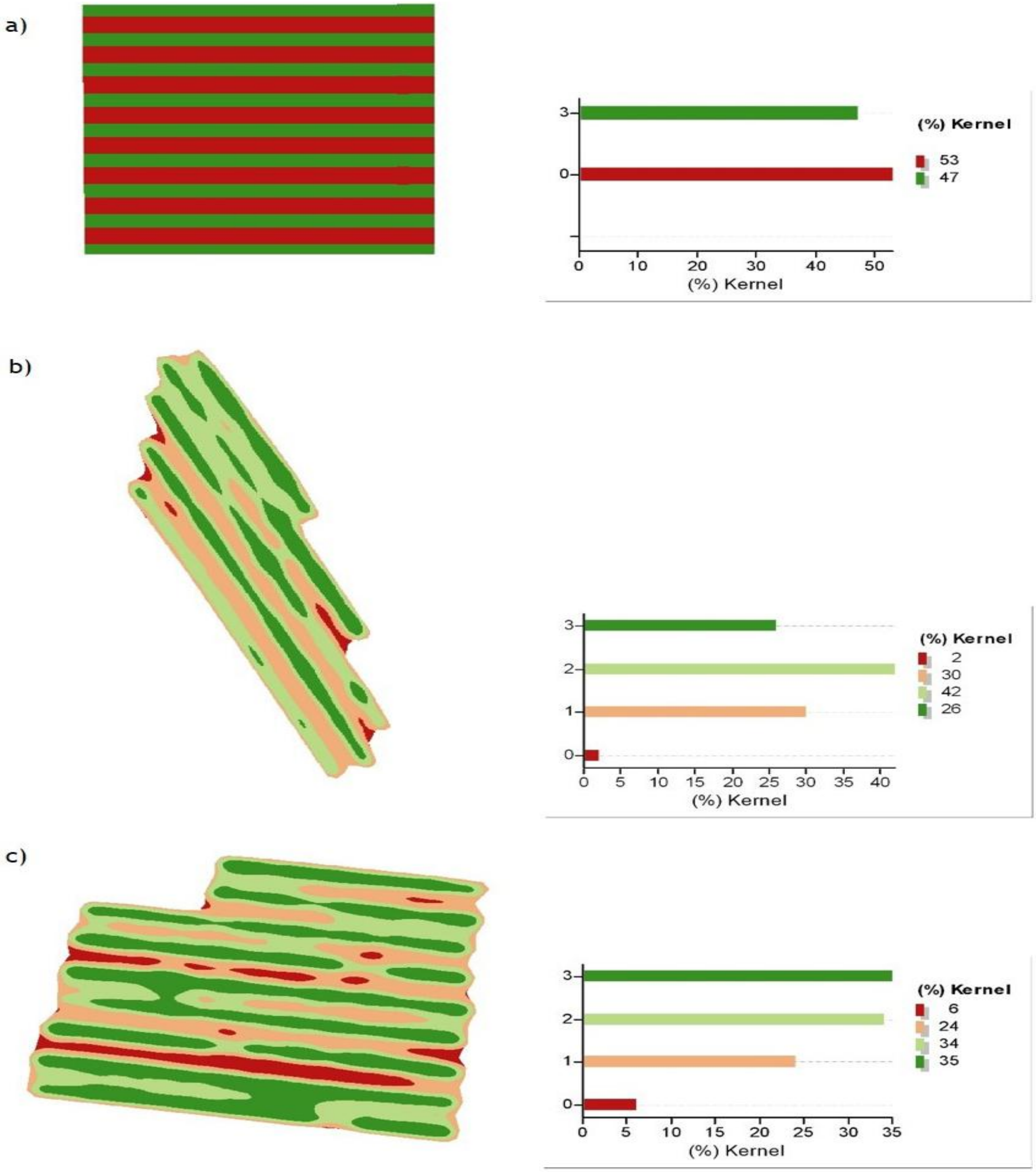
Figure 8 - Graphs of Statistical Process Control (SPC) for coffee planting (system semi-mechanized). Y-axis: variations of distances between planting lines in meters, X-axis: sampling points. a) Averages of observations, and b) Standard deviation of samples. UCL: Upper control limit and LCL: Lower control limit



Thus, Spacing errors are expected in plantations with low-tech platforms. Additionally, several factors may have occurred for low operation quality, such as tractor skidding, operating speed, hydraulic system clearance, and platform displacement.

Data from SPC charts are very relevant in planting planning, as special causes can be studied and corrected in future operations. In addition, data analysis and interpretation over time, regardless of normality condition, are necessary to level better management quality of machines and

Figure 9 - Density map, a) theoretical planting, b) manual planting, and c) semi-mechanized planting on a 1/500 scale in a cultivated field with arabica coffee



equipment (VOLTARELLI *et al*., 2015). Monitoring coffee crops on slopes through RPAs and SPC, Santana *et al*. (2021) verified differences in distances between planting lines even on low slopes. The authors related the errors to adjustments in the semi-mechanized system.

Planting density

Density maps are shown in Figure 9. Theoretical planting in Figure 9a presents a 3-m spacing between planting rows and 0.5 m between plants, represented by classes 0 and 3, respectively - kernel density estimation aids in studying point data spatial behavior. By color intensity and values presented in kernel maps, it is possible to identify planting errors (Weber; Wollmann, 2016).

Evaluated systems, manual and semi-mechanized, presented two classes not found in the control map (Figure 9a). So, classes 1 and 2 can be considered planting errors, as they are not observed in the theoretical planting map.

In both systems, the errors can be related to furrow preparation since furrow alignment error provides a planting misalignment. Comparing theoretical planting maps with analyzed planting systems, the manual one (Figure 9b) reached 26% of the desirable row spacing (class 3), and the semi-mechanized one (class 3) got 35% of it. Even though the latter system presented the number of transplanted plants below expected, it was observed by density maps the best plant distribution uniformity in this planting system.

Final considerations

Although the manual planting system presented fewer points outside calculated limits, average variations are high. Therefore, few improvements can be made to this planting system. The variations found in the semi-mechanized system are from special causes; thus, errors can be excluded or adjusted in the following plantation. Improvements in semi-mechanized systems make this operation more acceptable in the face of high-costs-coffee-growing implantation with mechanized systems.

Divergent performance views in the implantation systems in a study by Cunha *et al*. (2015) must be considered because they addressed operating costs in three planting systems: mechanized, semi-mechanized, and manual. Their results confirmed the elevated investments of BRL 580 ha$^{-1\ \text{for}}$ the manual operating system, followed by semi-mechanized with BRL 541 ha^{-1} and mechanized with BRL 471 ha^{-1}.

Some managements used in coffee growing are feasible in replacing human labor with mechanized operations since it allows greater practicality, optimization, and cost reduction (CUNHA; SILVA; DIAS, 2016). Also, work capacity combinations and more significant system efficiency result in lower operating costs (JANINI, 2007).

As obtained by this study, crossing the results can reinforce planting error identification and define causes, enabling corrections in the following operations. System improvements in the semi-mechanized one are necessary since variations from special causes were found in the process and presented in SPC charts. In the semi-mechanized system, it was noted that low planting density was high due to failure amount and misalignment.

CONCLUSIONS

1. Errors in the alignment and distribution of plants were identified in both planting systems under study. However, manual planting provided better performance in plant distribution;
2. Evaluating the spacing between plants in the row by SPC observed variations from special causes in both planting systems. However, the semi-mechanized system presented fewer average variations. Thus, after adjusting the considered points, the semi-mechanized system can perform better;
3. Evaluating spacing between planting lines by SPC found points from special causes in both systems. This analysis showed that the manual system presents a higher average variation despite having fewer points outside the control limits. In the semi-mechanized system, despite variations exceeding the upper and lower limits, there is a trend. Thus, adjustments to this system can contribute to better performance.

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