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SPATIAL VARIABILITY OF NOISE GENERATED BY A SELF-PROPELLED COFFEE HARVESTER IN AN OPEN AREA

José A. R. da Silva[1], Rodrigo L. Manzione[1,4], Geraldo G. de Oliveira Junior[3], Adriano B. da Silva[1], Fernando F. Putti[1*,4]

[1*]Corresponding author. São Paulo State University (Unesp), School of Sciences and Engineering/Tupã - SP, Brazil. E-mail: fernando.putti@unesp.br | ORCID ID: https://orcid.org/0000-0002-0555-9271

KEYWORDS

coffee harvest, mechanization, occupational risk, mapping.

ABSTRACT

Despite the advantages in production, mechanization may expose workers to high noise levels in the work environment, which is considered one of the main causes of work-related hearing loss. In this sense, this study aimed to analyze the spatial variability of noise generated by a self-propelled coffee harvester in an open area to define safe zones for operators and workers involved in coffee harvesting activities. The noise source used was an Electron Auto TDI self-propelled coffee harvester (model MWM D229-4), with a cabin manufactured in 2012 and a 67-hp 4-cylinder engine, working at 1200-rpm rotation. The noise level was measured by a digital decibel meter at points distributed within a regular 2.5 x 2.5 m sampling mesh (32.5 x 35.0 m area) surrounding the harvester in operation, which was configured according to the regulatory standard. Noise level spatial dependence was analyzed through geostatistics, characterizing structure and magnitude, and mapping spatial variability. Results showed that noise levels were above the limit established by relevant legislation (i.e., 85 dB), both for operators and employees at a distance of about 5.5 m from the generating source.

INTRODUCTION

Brazil is the largest producer and exporter of coffee in the world, producing 47.716 million 60 kg bags in 2021. The country is also the second largest consumer of this product. Therefore, coffee is one of the main crops in the country (CONAB, 2021; Hajjar et al., 2019; Pham et al. 2019).

Despite its advantages, the use of mechanized equipment in agriculture may expose workers to occupational hazards. Among them, physical noise agents stand out and vary with the level found, thus compromising occupational health (Costa et al., 2020). In coffee harvesting, many activities that had been previously performed manually became mechanized to optimize processes and hence reduce production costs (Matiello & Gonçalves, 2018; Silva et al., 2013). In turn, the use of mechanized equipment has daily exposed workers to various occupational risk agents such as noise, vibrations, and heat (Oliveira Júnior et al., 2022).

Exposure to occupational hazards such as excessive noise can lead to a loss in the quality of the employee's work performance, which even results in a compromise in their quality of life and health, including illnesses and accidents at work (Ribas & Michalowski, 2017). It is observed that noise can cause respiratory, psychological, cardiovascular damage, fatigue, sleep disorders, irritability, and immune system dysfunctions, directly affecting the quality and performance of work activities and also significantly increasing the possibility of work accidents, in addition to hearing loss that can be aggravated over the years (Ciqueira et al., 2020; Costa et al., 2020; Silva et al., 2014). According to FUNDACENTRO (2018), the investment in hearing conservation programs mainly aimed at controlling the emission of noise at the source is justified not only by maintaining the worker's hearing health but also by decreasing the workers' chance to suffer an accident.

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[1] Section of Agricultural Sciences, University José do Rosário Vellano (UNIFENAS) - Alfenas/MG, Brazil.

[2] Biosystems Engineering Department, School of Sciences and Engineering, São Paulo State University (UNESP) - Tupã/SP, Brazil

[3] Brazilian Federal Institute of Education, Science and Technology of the South of Minas - Muazambinho/MG, Brazil.

[4] Post graduation program in Agricultural Engineering, School of Agriculture, São Paulo State University (UNESP) - Botucatu/SP, Brazil

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According to Costa et al. (2020) and Cirqueira et al. (2020), noise consists of a mixture of unpleasant sounds; it is classified as a physical agent whose unit of measurement is the decibel (dB) and may be capable of causing irreversible damage over time.

Therefore, to prevent health problems and protect workers, these agents must be qualitatively and quantitatively evaluated in the work environment (Anaya Aguilhar et al., 2018; Balkhyour et al., 2019).

Depending on the generating source, noise can disperse in the work environment to different distances. Studies on environmental and occupational noise from different agricultural machines at different distance radii have shown variations in noise levels that can be harmful to the hearing health of operators, which must wear adequate hearing protectors (Iida & Buarque, 2016; Silva et al., 2021). As noise disperses and its levels vary in the environment as a function of its generating source, studies on sound-pressure spatial distribution become extremely relevant to establishing safety parameters in agricultural environments (Silva et al., 2021; Yanagi Júnior et al., 2012). Coffee harvest can be fully or semi-mechanized, with the use of manual work in activities such as sweeping, shaking, and collecting beans. Therefore, workers performing these activities may be exposed to noise levels above what is allowed by law (Silva et al., 2021).

Geostatistical analysis of spatial data can estimate the spatial continuity of processes, optimizing the interpolation functions for an accurate mapping of an agent (Issaks & Srivastava, 1989). For this purpose, the spatial distribution of this agent is assessed, through geospatial modeling and kriging interpolation, a weighted estimator with minimum variance and constant mean. This interpolation provides a more precise noise map, which can be used to reduce harmful effects on operators and helpers working near the source of sound pressure (Ferraz et al., 2013; Ferraz et al., 2016).

In this sense, the present study aimed to evaluate the spatial variability of noise generated by a self-propelled coffee harvester parked in an open area, using geostatistical analysis for observation and definition of safe zones for operators and workers involved in operational activities in the surroundings.

MATERIAL AND METHODS

Study area

The present study was conducted at the farm *Fazenda São Manoel*, in the city of Muzambinho, Minas Gerais State (Brazil) (21º 21' 31" south latitude, 46º 33' 03" west longitude, and 1,069-m altitude). The experiment was carried out on a coffee-drying terrace, where a self-propelled coffee harvester was parked. The search area was free of obstacles.

The sampling area had 32.5 x 35.0 m with a central point defined as coordinate 0.0. At this point, the harvester remained parked and in operation. The other points were distributed on a uniform square grid of 2.5 x 2.5 m around the equipment, totaling 210 points (Figure 1). At each end, four repetitions were sampled, with an interval of 5 seconds, totalizing 840 samples. For the subsequent analysis, each sample point average was considered.

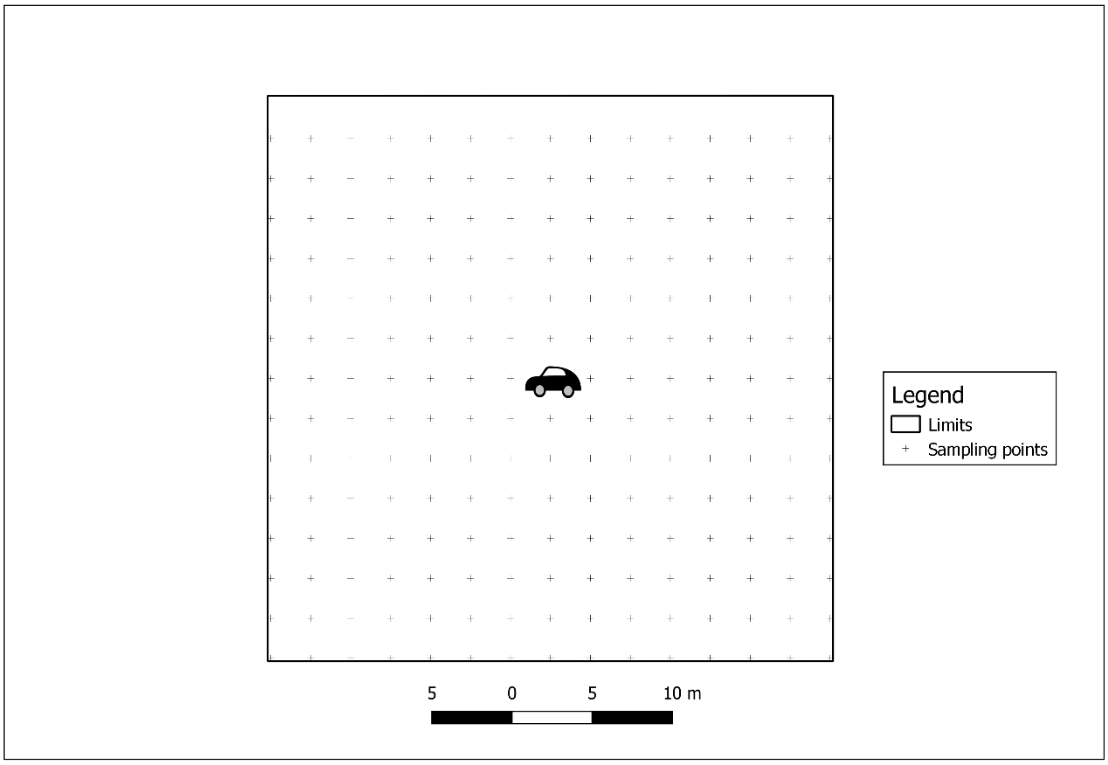

FIGURE 1. Limit of the study area, distribution of noise sampling points and positioning of the automotive harvester.

Rated equipment

The machine evaluated was an Electron Auto TDI self-propelled coffee harvester (model MWM D229-4), with a cabin manufactured in 2012 and a 67-hp 4-cylinder engine, working at 1200-rpm rotation. This rotation consists of an average for field bean collection operations (Figure 2).

FIGURE 2. Electron Auto TDI automotive harvester.

Source: www.tdimaquinas.com.br.

Noise assessment

Noise levels emitted by the harvester were assessed using a digital decibel meter (model HDB-900, Hikari brand). This equipment was calibrated electromechanically (Brazilian Calibration Network - RBC) by field measurements using a CAL - 4000 INSTRUTHERM IEC 942/CLASS 2 calibrator. Output sound pressure levels were 94 and 114 dB, which were configured by a “slow” response circuit, an equalization curve A, and expressed as dB (A), using a wind protector. Data were collected at the average height of a worker's ear (Brasil, 2014).

Geostatistical analysis

Noise spatial dependence was verified as the method described in Issaks & Srivastava (1989) and applied by Missio et al. (2015); Ferraz et al. (2016); and Lundgren et al. (2015). The method consisted of a variography, data interpolation by ordinary kriging, and cross-validation of results. GS + software was used for geostatistical analysis (GAMMA DESIGN SOFTWARE, 2004). An additional map layout was performed using the QGIS software package (www.qgis.org).

- **Structural analysis (variography)**

In the structural analysis, the spatial dependence structure of the sample data is verified. The geostatistical estimator of the spatial dependence of the data, known as semivariogram, can be estimated using the equation:

$$\hat{\gamma}(h) = \frac{1}{2N\,(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \qquad (1)$$

Where:

$N(h)$ = the number of measured value pairs $Z(x_i)$, $Z(x_i+h)$, separated by h.

According to Ferraz et al. (2016), the graph versus the corresponding values of h, called semivariogram, is a function of the vector h and, therefore, depends on both the magnitude and direction of h, illustrating the relationship between the variance of the samples and their lateral distances. The lateral distance between the models is estimated to optimize the number of samples and their variance. The distance at which the semivariogram reaches a stability value is called range (A_0), the limit of spatial dependence. The value close to the variance of the data is called the sill (C_0 + C). The range of spatial dependence represents the distance at which the sample points are correlated with each other. The points located in a larger radius area are independent, presenting a random and less homogeneous spatial distribution. It is called the nugget effect (C_0) as the distance (h) tends to zero, and the variation generally approaches a finite value. According to the same authors, this is an important parameter of the semivariogram since it represents the residual and random variation, not removed by close samples.

The variographic studies were processed considering adopting 0°, 45°, 90°, and 135° directions, constructing directional and omnidirectional semivariograms. Omnidirectional semivariograms are usually considered in one of the two or both of the following situations: (i) similar directional semivariograms (isotropy situation represented by a single omnidirectional semivariogram); (ii) scarcity of data and directional semivariograms that are too erratic. Then, both semivariograms were superimposed to detect occurrences or not of uneven spatial continuity in one or more directions. The preparation of these semivariograms was preceded by considerations about the distance from the sample field (L), where the value of $L\ /\ 2$ was used to calculate the experimental semivariogram, divided into 12 steps (lags), with an angular tolerance of 22.5 °. Anisotropy relationships (represented geometrically by an ellipse oriented with axes, according to the directions of greater and lesser continuity) were not detected. Then, the spherical, exponential, and Gaussian theoretical models were adjusted, looking for a theoretical model that best fits the studied phenomenon. The best semivariogram adjustment was measured by ordinary least squares (OLS) method.

- **Data interpolation**

Ordinary kriging was the geostatistical interpolation method used to build the map with the spatial variation of the noise levels generated by the coffee harvest machine. With the use of this interpolator, one of the central objectives of studies on spatial variability can be achieved, which is to obtain, from punctual observation, information for larger areas and points not observed, based on the observations of the variable to be estimated in non-sampled locations. Assuming one wants to estimate values, z^*, for any location, x_0, where there are no measured values, considering second-order stationarity (the variance cannot increase indefinitely) and that the estimate must be a linear combination of the values measured, the estimator will be:

$$Z^*(x_0) = \sum_{i=1}^{N} \lambda_i \, Z(x_i) \tag{2}$$

Where:

Z*(x_0) = attribute value estimated at point x_0;

N = the number of measured values, z(x_i), involved in the estimate, and

λ_i = the weights associated with each measured value, z(x_i).

Kriging is a weighted linear estimator that calculates the value of the weights by estimating the spatial structure of the distribution of the variables, considering the local average of the values in the estimates for non-sampled locations in the domain of the studied area. According to the spatial variability expressed in the semivariogram, the weights are variable, being nothing more than a weighted moving average, making it an optimal interpolator for the way the weights are distributed. But for the estimator to be optimal, it cannot be biased and must have minimal variance. The non-trend condition means that, on average, the difference between estimated and measured values for the same point must be zero. The condition of minimum variance means that, although there may be differences, point by point, between the estimated and the measured value, these differences must be minimal. This statistical interpolation is identical to multiple linear regression (MLR), with some differences regarding the use of the matrices used to solve the systems (Yamamoto, 2010).

- **Cross-validationon**

Semivariograms adjustment can be evaluated by the technique known as cross-validation, which allows the impact of different models of semivariograms on the results of interpolation to be compared, removing the current data and re-estimating them by the data from the neighbors that remained (Goovaerts, 1997). According to Manzione (2018), it is important to have a means to check if the model is adjusted, whether it is satisfactory or not, and to validate the kriging plan before its use in the construction of maps. In this study, semivariograms were evaluated by the cross-validation technique using the Average Standard Error (ASE) as a measure of the interpolator performance, considering this value should be close to the mean standardized (zero).

RESULTS AND DISCUSSION

Data exploratory analysis by descriptive statistics (Table 1) showed a great variation in environmental noise. It could be verified by differences between maximum and minimum noise levels. The maximum level found exceeded the daily exposure limit (100%) of 8 hours of exposure at 85 dB, according to Regulatory Norm NR-15 (Brasil, 2014).

TABLE 1. Descriptive analysis of the data for noise generated by the automotive coffee harvester in decibels (dB).

Equipment	Noise level dB									
	Min.	Max.	$\bar{x}$	Md	Mo	K	AS	S	ASE	CV
Automotive harvester	66.70	92.80	75.00	73.80	72.70	1.74	1.29	4.85	0.33	6.46

Min. - Minimum value; Max. - Maximum value; $\bar{x}$ - Average; Md - Median; Mo - Mode; K - Kurtosis; AS - Asymmetry; S - Standard deviation; ASE - Average Standard Error; CV - Coefficient of Variation.

An approximate normal probability distribution was identified for the observed values, in which mean, median, and mode had values close together. Kurtosis and asymmetry coefficients were 1.74 and 1.29, respectively, which indicates a leptokurtic distribution. It was more tapered with a higher peak than the normal distribution, as well as positively asymmetric with a tail on the right side slightly longer than the left side. Data variability was considered low, with a standard deviation of 4.85 and a coefficient of variation of 6.46%. Therefore, the exploratory analysis results provide enough conditions for the determination of spatial dependence by geostatistical analysis, considering a second-order stationarity hypothesis.

Geostatistics was used to verify noise dispersion spatial dependence since it provides accurate information for further interventions to ensure safety, increase productivity, and preserve workers' health (Silva et al, 2014; Silva et al., 2021). Figure 3 shows the graphical representation of semivariance as a function of distance h and the theoretical model fitted to experimental data for noise from a self-propelled coffee harvester.

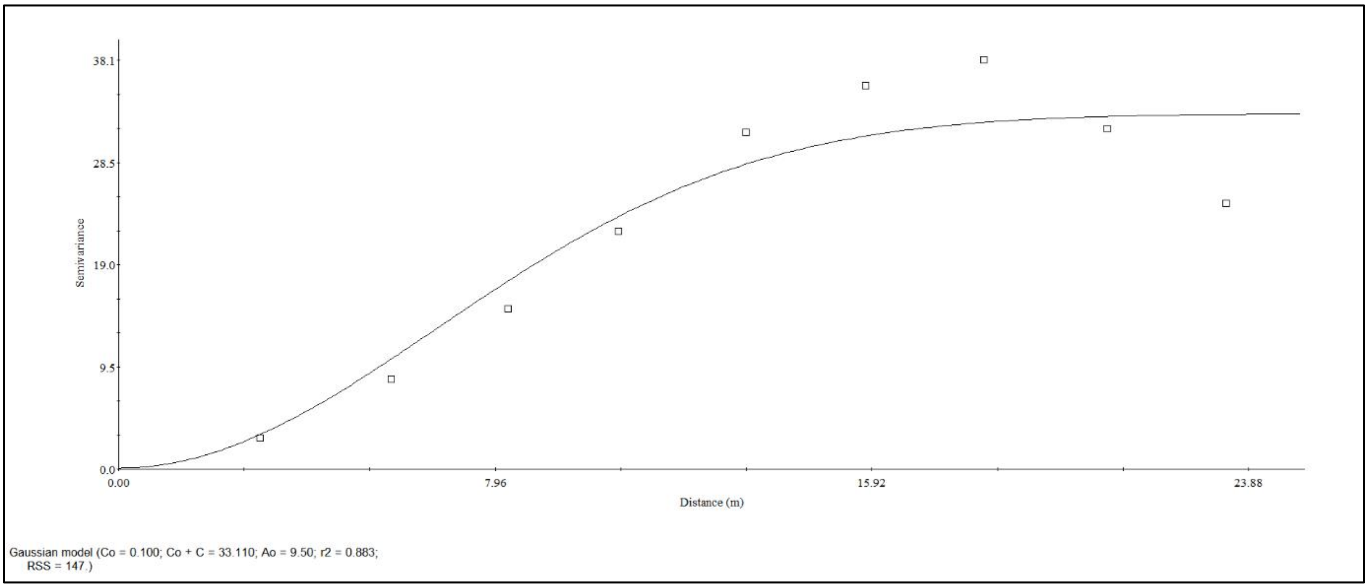

FIGURE 3. Experimental semivariogram of the noise produced by an automotive coffee harvester and Gaussian model adjusted by the method of ordinary least squares (OLS).

Table 2 shows that noise levels from the self-propelled coffee harvester had semivariogram parameters fitted to a Gaussian model.

TABLE 2. Semivariogram parameters adjusted to the noise level data generated by an automotive coffee harvester.

Model	C_0	$C_0 + C$	A_0	r^2	DSD (%)
Gaussian	0.100	33.110	9.50	0.883	99.69

C_0 - nugget effect; $C_0 + C$ - threshold; A_0 - range (m); r2 - model determination coefficient and DSD - Degree of Spatial Dependence $(C / C_0 + C) \times 100$.

Geostatistical analysis showed that the spatial dependence degree (SDD) of noise levels was strong, according to Biondi et al. (1994). These authors established three spatial dependence intensities: weak (SDD ≤ 0.25 - 25%), moderate (SDD between 0.26 and 0.75 - 26 to 75%), and strong (SDD > 0.75 - 75%). Since we found an SDD of 99.69%, one can say that sound pressure level has a great influence on the location and space around the machine. Likewise, Ferraz et al. (2013) analyzed the spatial variability of noise from a portable harvester in coffee plantations and found an SDD of 92.86% (strong), but using a spherical model.

A range (A0) of 9.50 m was observed. It defines the distance from coordinate 0.0 showing spatial dependence (Table 5). Thus, from this distance onwards data will have a random spatial distribution, becoming independent of each other (Missio et al., 2015). Spadim et al. (2015) also found spatial dependence for agricultural tractors working at different engine speeds, but with a minimum range of 22.89 m. We observed a nugget effect (C_0) of 0.10 (Table 2), which presupposes the absence of analytical errors, sampling errors, or natural effect of the studied phenomenon; therefore, data collection for analysis was suitable (Lundgren et al., 2015).

Figure 4 shows the cross-validation adjusted to noise level from the self-propelled coffee harvester (dB) as a function of sampled point distance.

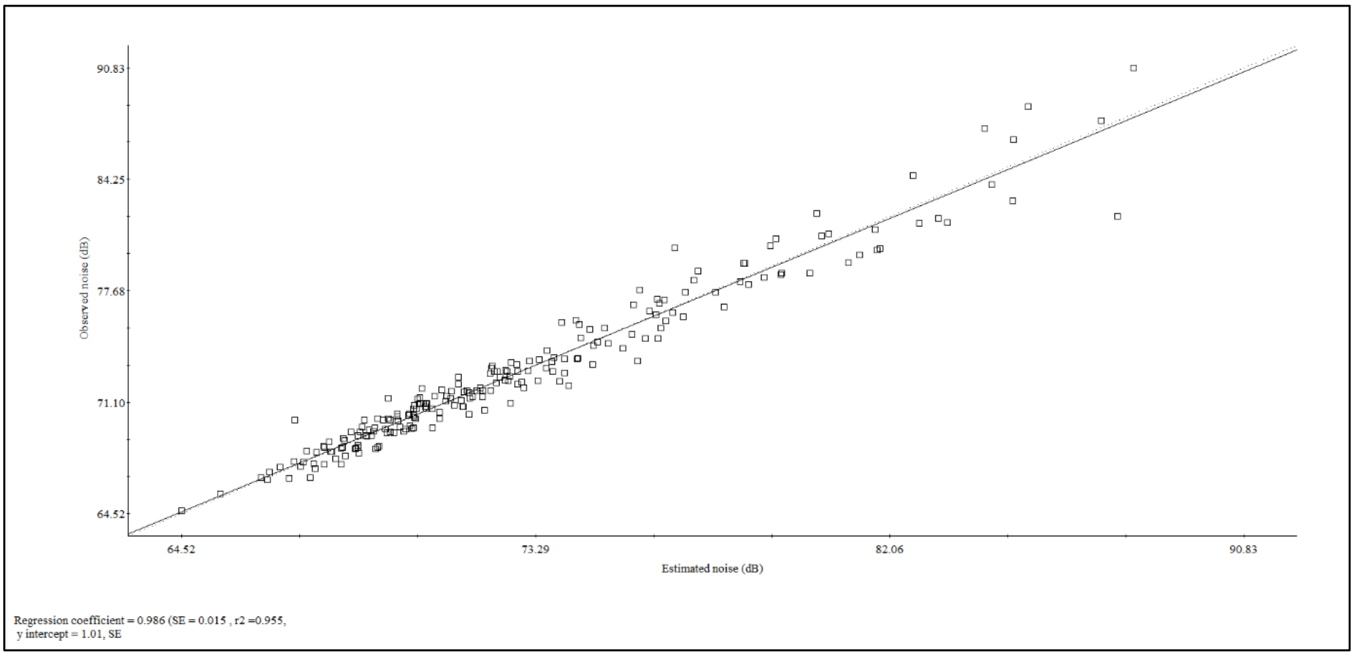

FIGURE 4. Cross-validation parameters for the semivariogram adjusted to the noise data generated by an automotive coffee harvester (dB).

Therefore, a 45° line was practically equal to the adjusted line, regression coefficient (slope) obtained was 0.98, with a standard error of 0.01 and r^2 (coefficient of determination) of 0.95, representing a good adjustment accuracy. Also in Figure 4, the farthest points from the line are concentrated at the end, as semivariograms often provide better estimates for shorter distances. According to Issaks & Srivastava (1989), this is due to the smoothing effect of the ordinary kriging estimator, which tends to have greater errors in the outliers of the data distribution.

Ordinary kriging proved to be efficient to estimate unsampled values, using a semivariogram fit (Figure 5). Therefore, a spatial distribution map of noise can be built, and the variability can be better visualized (Oliveira et al., 2015).

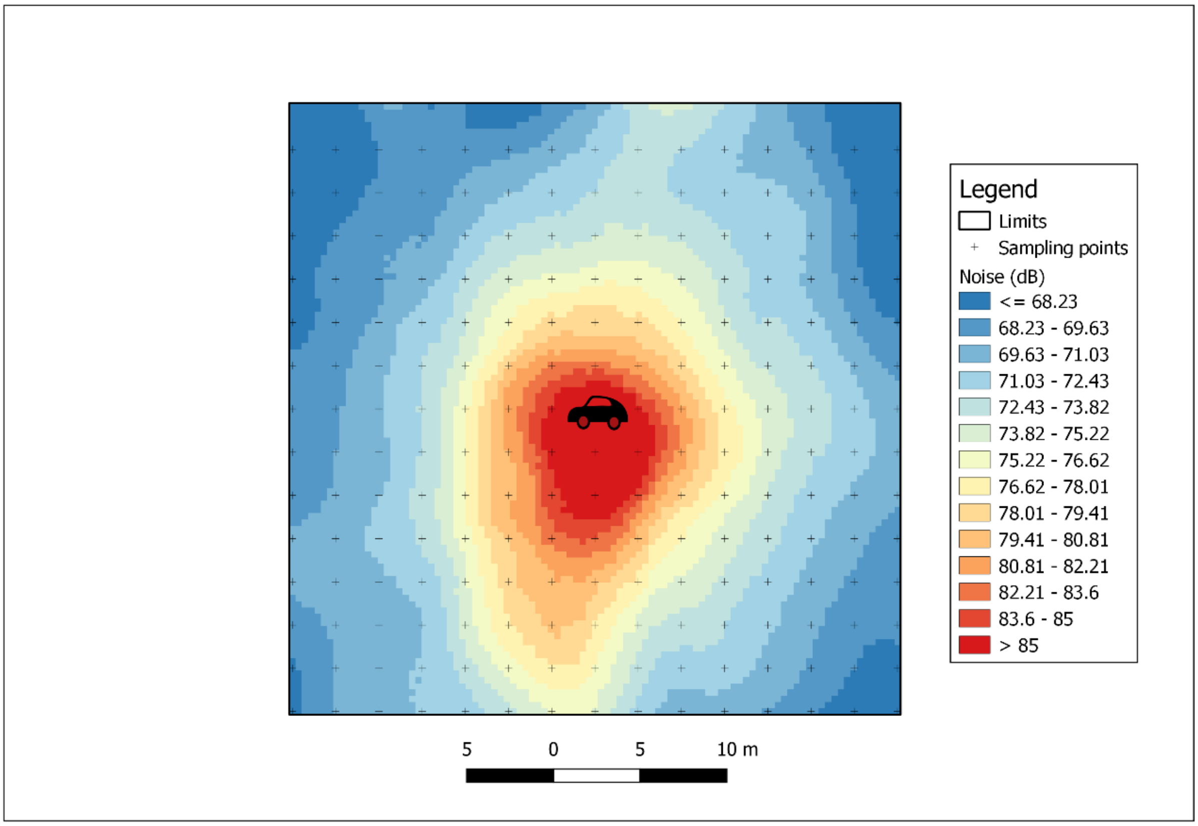

FIGURE 5. Spatial distribution of noise produced by an automotive coffee harvester dB in an area free of obstacles and frontal indication of the machine.

The map showed anisotropic behavior, that is, the sample semivariogram depends only on distance and not on direction; therefore, the semivariogram is the same in all directions. Figure 5 shows that noise decreases in all directions as distance increases, showing the distance effect on the sound pressure source. Moreover, points with higher noise levels are concentrated in the lower part of the map, that is, in the projection of the used equipment engine. Veiga et al. (2021) found a similar situation when analyzing noise distribution near agricultural and forestry machines. Likewise, Gonçalves et al. (2019) evaluated noise emitted by a cutting tractor through geostatistics, finding values of 7 m in front, 7 m on the right side, 5 m on the left side, and 3 m at the rear of the evaluated equipment.

According to Figure 5, the safe distance for workers around the machine was around 3.0 m in front and rear, 2.5 m on the right side, and 7.5 m on the left side. This projection of the engine starts from the sound pressure source, where the average noise level reaches the maximum allowed by current legislation (85 dB for 8 hours a day). Therefore, workers must wear personal protective equipment (PPE) to avoid damage to health and to improve well-being at work.

Figure 6 shows the reclassification of the values interpolated by ordinary kriging in relation to the safe area for the worker (noise <85dB) and with excessive noise (noise ≥ 85dB).

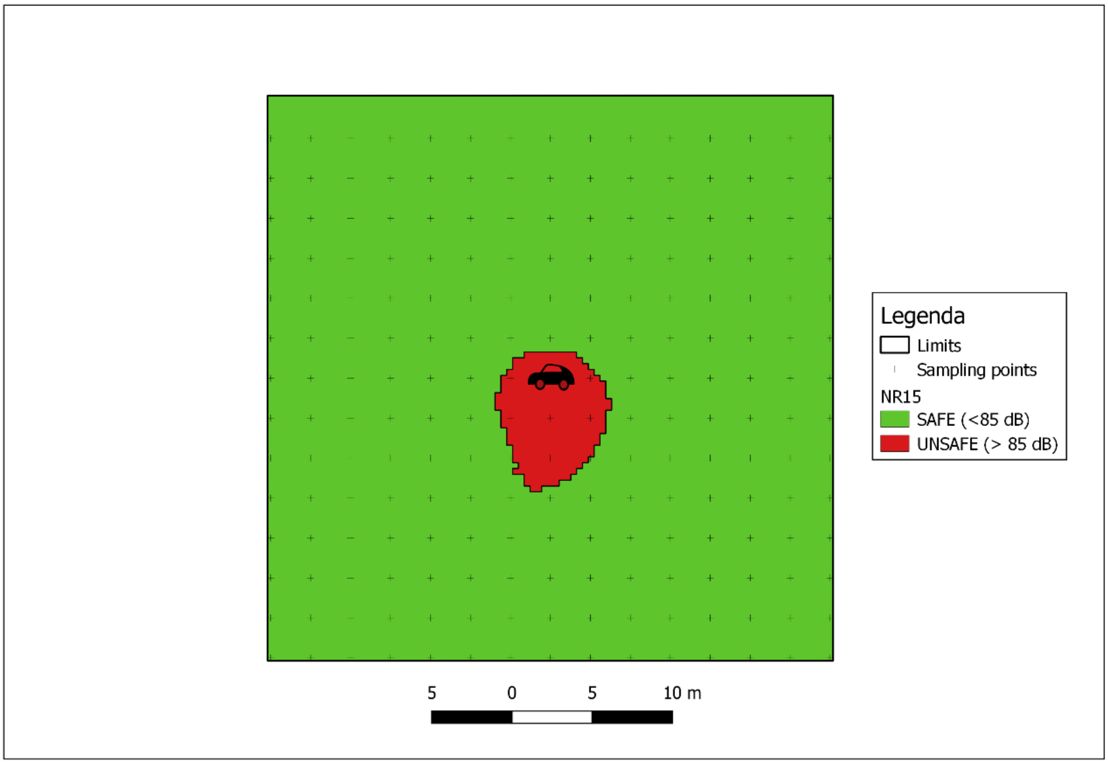

FIGURE 6. Safe and insecure areas regarding the representation of the noise produced by an automotive coffee harvester.

As it can be seen in the reclassified map, the machine operator is more exposed to the noise levels generated, subject to damage caused by this physical agent, since the noise in the red area exceeds the limit established in NR 15. The risk area of the classified map was 45.60 m^2 around the machine. Therefore, in accordance with NR 15, the workers need PPE for the performance of their activities close to the machine or in that surrounding area, since the maximum values of measured noise reached 92.80 dB. Also from the map in Figure 5, it is possible to define a radius greater than 5.50 m as the limit of approach of workers in relation to the machine. Thus, the operator exposed to this noise level, could only work for 75,59 minutes without adequate protection (FUNDACENTRO, 2001).

It is noteworthy that the NHO 01 is more protective in relation to the NR 15, due to the increase in the doubling of the dose (q) used, following the international standards of criteria, and, if we compare with the time allowed by the NR 15, it would be 160 minutes (ACGIH, 2018; FUNDACENTRO, 2001, Brasil, 2014).

Spandim et al. (2015), when they evaluated the spatial dependence of noise from agricultural tractors at different engine speeds, they also found noise levels above that allowed by the current legislation, which is 85 dB for an 8-hour day, and a strong spatial dependence on the sampled values. It is also possible to visualize on the maps, a safe distance to operators and workers around the machines.

In studies to assess noise levels in agricultural tractors, Silvestrini et al. (2015) concluded that the noise level is higher the closer to the tractor engine exhaust, and even at a distance of 4 m from the source, the sound pressure level exceeded 85 dB. Also according to the same authors, it is common for the operator to use personal protective equipment only, not worrying about the workers around the equipment, when in operation. Thus, it can be said that, according to the results presented, the use of PPE is mandatory, not only for the machine operator, but for all workers who are within the area considered hazardous.

CONCLUSIONS

Noise levels showed a strong spatial dependence degree, modeled by semivariogram with a range of 9.50 m.

The map of isolines was built by ordinary kriging interpolation, enabling visualization of spatial variability of noise from the self-propelled coffee harvester, homogeneously dispersed around the implement.

The geostatistical analysis allowed determining a safe distance for workers around the harvester. Workers at distances of up to 5.50 m around the equipment may suffer harmful effects from generated noise. Therefore, they should wear hearing protectors to avoid long-term hearing damage.

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