ENGINEERING SCIENCES

Characterization of noise emitted by a low-profile tractor and its influence on the health of rural workers

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Abstract: Noise is one of the main physical agents in the rural work environment and it can be harmful to the health of workers exposed to it. Thus, research on the spatialization of noise emitted by agricultural machinery can help minimize harmful health effects. This study sets out to evaluate the spatial distribution of the noise emitted by an agricultural tractor with and without the activation of a rotary cutter. A wave model geostatistical analysis was used to identify healthy working zones according to current legislation. The experiment was carried out using a 75 hp tractor at 2000 rpm with the rotary cutter on the on and off modes. A digital sound level meter was used to register noise in a regular 2.0 x 2.0 m sample mesh within a 10-meter radius. The semivariogram was adjusted using the weighted least squares method, wave model and kriging interpolation to obtain the maps. The magnitude and spatial structure of the noise emitted by the tractor were identified. The results show that the equipment produced noise levels above the limits recommended by Brazilian regulatory standard NR 15. Thus, both the machine operator and the workers involved in the operation should use Personal Protective Equipment.

Key words: agricultural machinery, ergonomics, kriging, noise, safety in agriculture, spatial variability.

INTRODUCTION

Agricultural mechanization has allowed for higher efficiency in operations that were previously done manually (Veiga et al. 2014). With the coming of machinery, mankind has produced more in shorter periods and manages agricultural operations with more precision (Veiga et al. 2015). However, farmworkers had to adapt themselves to perform their activities, risking their health and safety.

Poje et al. (2016) stated that in this adaptation, man-machine, mainly the agricultural worker, are exposed to several health hazards such as noise, vibration, and exposition to gases and particles. Also, many times these workplaces have no monitoring and training, which further exacerbates the situation, causing damage to the health of workers involved in these agricultural operations.

According to Cunha & Teodoro (2006), noise is one of the leading causes of health damage of laborers, and it contributes to a rise in stress and discomfort levels in farm work. It can also lead to work-related accidents and lower capacity to operate. Moreover, according to Nelson et al. (2005) and Vallone et al. (2016), excessive noise is a global occupational health hazard with considerable social and physiological impacts, including noise-induced hearing loss (NIHL). Lashgari & Maleki (2016) claim that farmworkers present higher rates of NIHL in comparison with

other professions. Such damage was identified lately in the agricultural industry (Nascimento et al. 2016).

Agricultural machine-emitted noise propagates in the environment; it becomes less intense with distance and can increase with the use of attachments such as rotary cutters, plows and offset disks (Magalhães et al. 2012). It becomes, hence, necessary to determine the spatial distribution of this noise to evaluate the healthiness of the work environment of machine operators and workers supporting the agricultural operation.

However, noise is considered a wave, and the most suitable models to adjust this type of data would be models that behave as periodic or sinusoidal functions, such as the wave model proposed by Webster & Oliver (2007). Therefore, models such as Gaussian, spherical, exponential could be not so suitable to characterize the noise wave behaviour.

In this scenario, this study sets out to evaluate the spatial distribution of the noise level emitted by a low-profile tractor with and without the use of attachments, through geostatistical analyses. The semivariogram was adjusted to the wave model for determination of healthy working zones.

MATERIALS AND METHODS

The experiment was carried out at the Technical School of the Federal Rural University of Rio de Janeiro (CTUR), Seropédica, Rio de Janeiro, Brazil. In this study, a low-profile tractor (no enclosed cabin, 55.16 kW, 75 cv) operating at 2000 rpm to guarantee 540 rpm at power take-off (PTO) was used. The tractor used in this experiment is suitable to operate the rotary cutter used in this analysis. It was evaluated with and without the activation of a rotary cutter (Figure 1).

The evaluation of the noise level for this agriculture tractor was done following the methodology described in the Brazilian regulatory standard NBR-9999 (ABNT 1987). The temperature and speed conditions measured were between 21.4ºC and 29.4ºC, and wind speed below 0.67 m.s^{-1} measured at the Seropedica/RJ meteorological station.

Noise levels were determined with sound level meters model DEC – 480 (Instrutherm, São Paulo, São Paulo). The sound level meter was
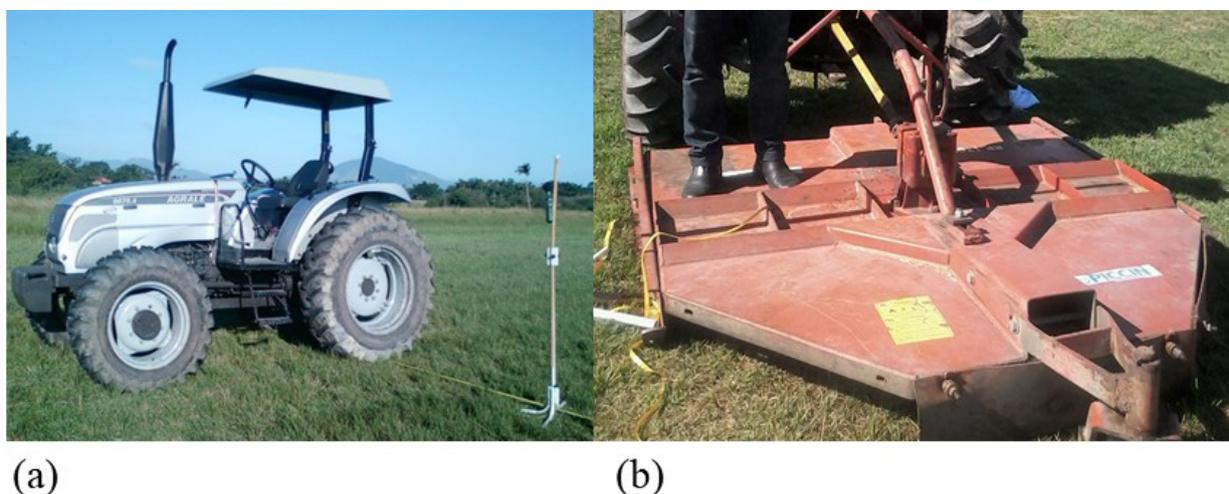

Figure 1. Agricultural tractor measured for noise levels: a) without activation of a rotary cutter; b) with activation of a rotary cutter.

calibrated at the beginning of the collections, using the digital acoustic calibrator, model CAL-5000, (Instrutherm, São Paulo, São Paulo). The configurations used were defined in the SLOW response and A frequency weighting, expressed in dB(A), as per Annex 1 of Brazilian regulatory standard NR 15 (Brasil 2019a). The windshield was used in all measurements.

Measurements were taken at the operator's ear level, in a 10-meter-radius 2.0m x 2.0m regular mesh. Each measurement was performed after the measurement stabilized in the time from 30 to 60 sec. The total number of points was 121, centered around the operating tractor. Spatial coordinates (meters) were arbitrated and their central point (0,0) corresponded to the operator's seat. The machine was operating during the complete data collection.

The dependency of the noise emitted by the tractor was assessed through the classic semivariogram adjustment, as described by Missio et al. (2015), with and without attachments. The semivariogram was adjusted using the weighted least squares (WLS) regression and the wave model, as described by Webster & Oliver (2007) (Equation 1). Those adjustment methods were the most adequate to describe the behavior of the phenomenon analyzed in this study.

$$\hat{\gamma}(h) = C_0^2 + \frac{a}{h} sen\left(\frac{h}{a}\right)^4 \qquad (1)$$

where, h is the distance between samples, C0 is the nugget effect, and a is the range.

A third-degree polynomial was used to remove the tendency that might interfere with the spatial dependency of the data. The semivariogram was generated from the remaining data (the difference between observed and equation-estimated values) according to the procedure used by Lundgren et al. (2015).

Following the adjustment of the semivariogram function, the interpolation of the residual data was performed through universal kriging. The trend map was subsequently created and added to the maps of residuals to create the map for noise distribution.

The cross-validation technique of Isaaks & Srivastava (1989) was used. The error evaluation technique allows for the comparison of predicted and sample data. This allowed the removal of parameters such as mean error, the standard deviation of mean errors, standardized mean error, and root-mean-square standardized error.

The statistics software R (R Development Core Team 2019), with the help of the geoR pack (Ribeiro Jr & Diggle 2001), was used for statistical analysis and construction of isoline maps.

The levels of noise determined by the NR 15 standard (Brasil 2019a) were adopted for the healthiness assessment. The free software QGIS version 2.14.15 (Quantum Gis Development Team 2019) was used to create the map's layout.

RESULTS AND DISCUSSION

The highest and lowest noise values, coefficient of variation, and average noise level emitted by the tractor with and without the activation of a rotary cutter (Table I) show data variability. This analysis alone, however, does not show where the extreme values occur, and a geostatistical analysis is necessary.

The analyses results – noise with and without rotary cutter activation – generated the semivariograms and their parameters (nugget effect-C_0; sill-C; range-a), which were obtained through the WLS and wave methods. They are shown in Table II and the semivariograms are illustrated in Figures 2a and 2b.

The spatial dependence existence was confirmed by semivariograms, both for tractor

Table I. Descriptive statistics of the noise emitted by a tractor without activation and with activation of a rotary cutter.

Tractor	Min	Max	n	x	Md	SD	Var	CV	K
without activation	68.10	90.70	121	75.25	75.00	4.031	16.247	5.36	1.078
with activation	74.00	93.10	121	80.26	79.00	4.266	18.196	5.31	-0.052

Min - Minimum value of the variable; Max - Maximum value of the variable; n- number of measurements; x - Average; Md - Median; SD - Standard deviation; Var - Variance; CV - Coefficient of variation (%); K - Coefficient of kurtosis.

without activation and with activation of a rotary cutter (Figure 2). This occurs when the experimental semivariogram stabilizes in a determined distance. This fact coincides with the work of Ferraz et al. (2013) and Spadim et al. (2015). According to Pyrcz & Deutsch (2003), the wave model is often used to indicate cycles or periodicity. As the noise is a sound wave, this model was very well adapted to the data, having a faithful adjustment to the cyclical behavior of the sound (Gonçalves et al. 2019).

Semivariogram analysis of noise shows the existence of spatial dependence up to 1.94 meters (Figure 2a) for the tractor without activation of a rotary cutter and up to 1.89 meters (Figure 2b) for the tractor with activation of a rotary cutter. These results corroborate the results of Gonçalves et al. (2019) that found a range for power tiller noise ranging from 1.81 to 1.85. It is noteworthy that these range values found in this study do not serve as a comparison with studies that used the estimation by kriging without removing the trend because, in this work, the semivariograms were adjusted based on the residues. Besides, the semivariogram was adjusted using a "wave" model. Thus, it is recommended that studies remove trends from the data and adjust the "wave" model to serve as a comparison.

The range "a" value found in the semivariogram of the tractor with activation of a rotary cutter was slightly less than the range of the tractor without activation of a rotary cutter. It means that with the activation of a rotary cutter, the spatial dependence is lower when compared to the spatial dependence of the tractor without the activation of a rotary cutter.

The wave model was accurate to describe noise data behavior (sinusoidal) and is the most adequate to characterize this type of data. A few studies on the spatial distribution of agricultural machine-emitted noise claim that Gaussian (Missio et al. 2015, Pimenta Junior et al. 2012, Spadim et al. 2015, Yanagi Junior et al. 2012) and spherical (Ferraz et al. 2013) models are the most adequate to adjust the semivariogram. Their results diverge from those obtained in this study; possible explanations can be the sample grid adopted, environmental effects, or the experimental design. The grid size can influence the range in addition to the effects of the environment, such as wind, can interfere with the data since the noise uses the environment to propagate.

Figure 3a shows that in the center of the map (0,0) - operator position - the noise level reached 90.7 dB (A) - the highest measured value that is represented by the dark red color. It is observed that in positions (2,2), (4,4), and

Table II. Estimated parameters of the experimental semivariogram for the noise level emitted by a tractor activation and with activation of a rotary cutter.

Tractor	C_0	C	a	ME	SD_{ME}	RE	SD_{RE}
without activation	1.00	4.11	1.94	0.01	1.14	0.00	1.05
with activation	0.85	3.22	1.89	0.02	1.03	0.01	1.01

C_0 – nugget effect; C - Contribution; C_0+C – Sill; a - range; ME - Mean error; SD_{ME} - Standard deviation of mean error; RE - Reduced mean error; SD_{RE} Standard deviation of reduced mean errors; WLS - Weighted least squares.

(10,6), the noise levels were 85.2, 81.1 and 78.8 dB (A), respectively. In the positions (-2,2), (-4,4) and (-10,6) the noise levels were 82.4, 78.5 and 73.7 dB (A) respectively. Thus it is noticed that the noise values emitted by the tractor with the cutter in the off mode presented higher noise levels, especially to the right where the engine gas outlet is located. The lowest noise value of 62.4 dB (A) was found in (-10.5, -10.5), represented in dark blue on the map.

Figure 3b shows that the noise level of the activated rotary cutter was also above 85 dB (A) around the machine. The value found was 91.2 dB in the operator's seat, position (0,0). The noise emitted by the cutter was 89.2 dB (A) at position (0, -5). The highest noise value was 93.1 measured at the position (0, 2) where the engine is located. In the rear, it was observed values above what is allowed by legislation. In the positions (4, -4), (-2, -3), and (3, -4) noise levels of 85.3, 88.02 and 86.9 dB (A) were found. The lowest value was 67.8 dB (A) found at position (10.5, 10.5), it was shown in dark blue on the map. It was because the noise level decreased as the distance increased from the source of noise (tractor), corroborating the results of Abood (2018).

Regulatory standard NR 31 (Brasil 2019b) states that employers of rural workers must follow ergonomic principles to adapt the working conditions to the psychophysiological characteristics of such workers in order to provide a safer and more comfortable work environment. Since the results found in this study are above the limit allowed by legislation and high noise levels are harmful to the operators' health, the NR 31 requires the use of ear protection for their activity.

Tractors with cabins offer noise protection and can be an alternative to the use of Personal Protective Equipment (PPE) because they attenuate the tractor sounds. Cunha et al. (2012) evaluated plowing tractors with and without cabins measuring the noise near the operator's ear. They concluded that the use of either earmuffs or cabins was required. Studies conducted by Baesso et al. (2015) showed that the average noise levels emitted by tractors with closed cabins were close to the accepted values established by the NR 15 for an 8-hour work journey. Safety measures and the use of PPE are necessary for tractors that do not possess cabins, which is the case of this study.

The values of noise emitted by the tractor with the cutter on the off mode, which was above 85 dB(A) are present in a 2-meter-radius area around the equipment (Figure 4a). The daily exposure is of 8 hours (Brasil 2019a). When the rotary cutter is activated, alarming noise values are observed, generally up to 4 meters away from
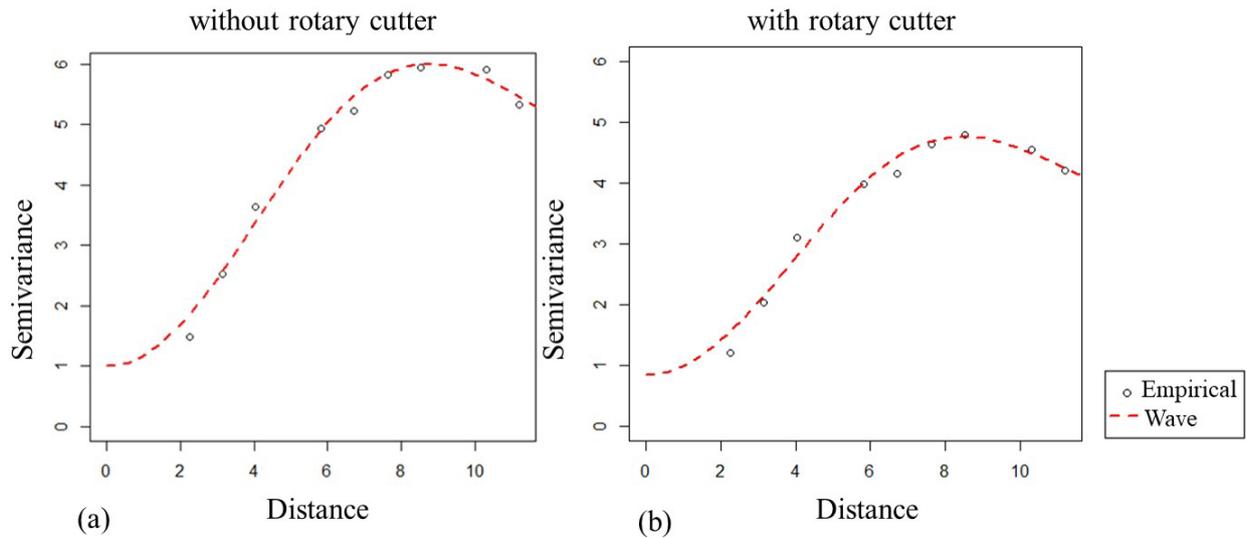
Figure 2. Semivariogram of the noise emitted by the agricultural tractor (a) without by a tractor activation of a rotary cutter (b) with by a tractor activation of a rotary cutter.

the right, front and left sides of the machine and 8 meters from the backside (Figure 4b).

The highest noise value for the tractor with the deactivated rotary cutter was 90.7 dB(A) on the operator's seat (0,0) (Figure 4a). The maximum exposure recommended by the NR 15 is of 3 hours and 30 minutes in those conditions (Brasil 2019a).

The highest noise values for the tractor with the rotary activated cutter was near the engine – source of the noise. Its value is 93.1 dB(A) in position (0, 2) and in the rotary cutter the noise level is 89.2 dB(A) in position (0,-5) (Figure 4b). The maximum daily exposure allowed by the NR 15 standard (Brasil 2019a) is of 2 hours and 40 minutes for such conditions.

This way, both the tractor operator and worker supporting the agricultural activities are subject to the harmful effects of noise emitted by this machinery, with or without an active rotary cutter. The use of protective equipment is recommended during all operations. Figure 5 illustrates the areas around the tractor where the use of hearing protectors is needed or not,

based on whether or not the noise levels are equal to or greater than 85 dB (A).

The operator who closes to the tractor without activating the rotary cutter must PPE, as well as those who will eventually support operation in a 2-meter radius. Regarding the cutter-attached tractor, the operator and all workers at up to 5 meters away from the front, 4 meters from the sides, and 8 meters from the back must make use of PPE. It was observed that the noise of the tractor with the rotary activated cutter was greater than without activate the rotary cutter. It is because the engine has to produce more power to overcome the increment of the implement, and it increased the noise.

According to the results shown in Figures 3, 4 and 5 and based on the acceptable noise values established by the NR 15 (Brasil 2019a), the determination of risk or acoustic healthiness zones is of fundamental importance for the management of agricultural machinery operation, for it promotes damage prevention and welfare of farmworkers.
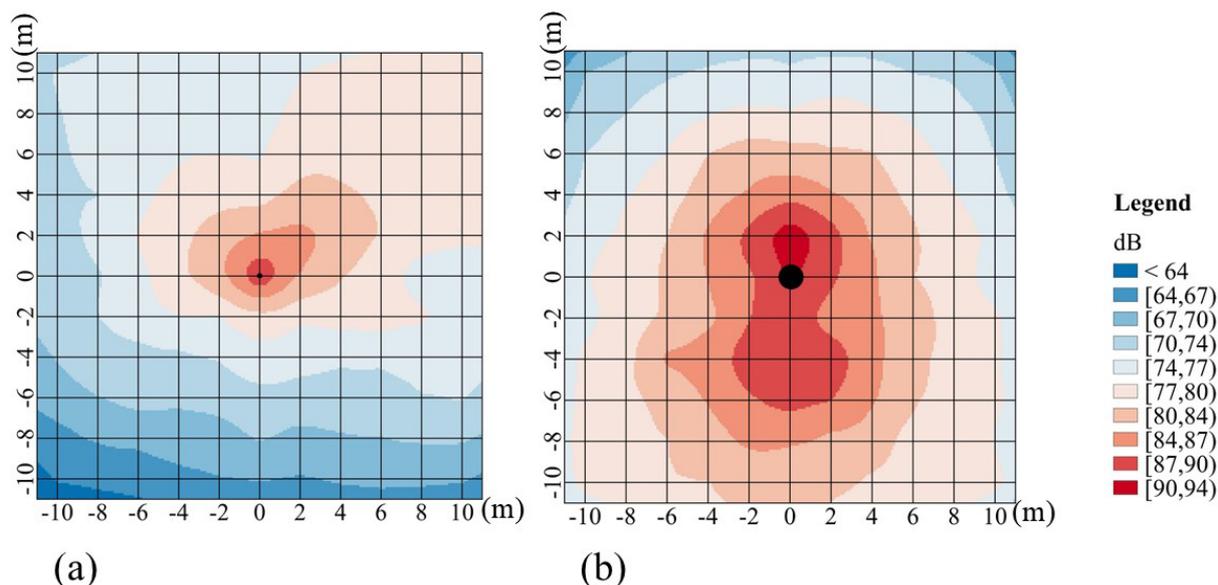
Figure 3. Map of the spatial distribution of noise emitted by the tractor. (a) without activation of a rotary cutter (b) with activation of a rotary cutter.

With this study, it was possible to determine the unhealthy zones in which the operator must or should not use personal protective equipment. It is known for the difficulty faced by workers regarding the use of PPE. Studies carried out by Menegat & Fontana (2010), report the conditions of rural work and confirm, through the reports, that the PPE protects the worker against occupational risks, however, they are used partially or neglected by the workers and / or employers, configuring the presence of risk of illness.

Thus, this study disables people who are in the healthy, blue area of the Figure 5 map, from wearing ear protectors since its use is a difficulty found in rural areas. It should also be noted that for proper protection, the choice of hearing protectors needs to be specific in size for each worker (Rodrigues et al. 2006, Machado et al. 2020). The use of other protective mechanisms such as cabins (Cortez et al. 2008, Cunha et al. 2012, Machado et al. 2020) are existential to minimize the risk of damage to the operator's hearing health. These measures provide lower noise levels, and consequently reduce fatigue and improve the concentration of agricultural workers (Bilski 2013).

A weak point of the study is that it was carried out for a specific type of tractor and implement. Therefore, these recommendations are not valid for everyone, being necessary to evaluate each tractor individually. Thus, different jobs, engine loads, speed, rotation, climatic and soil conditions, and operator skills must be taken into account (Solecki 1999). In addition to types of attachments, drive mode, operating regime, local working conditions (open or closed field), as these conditions vary from case to case.
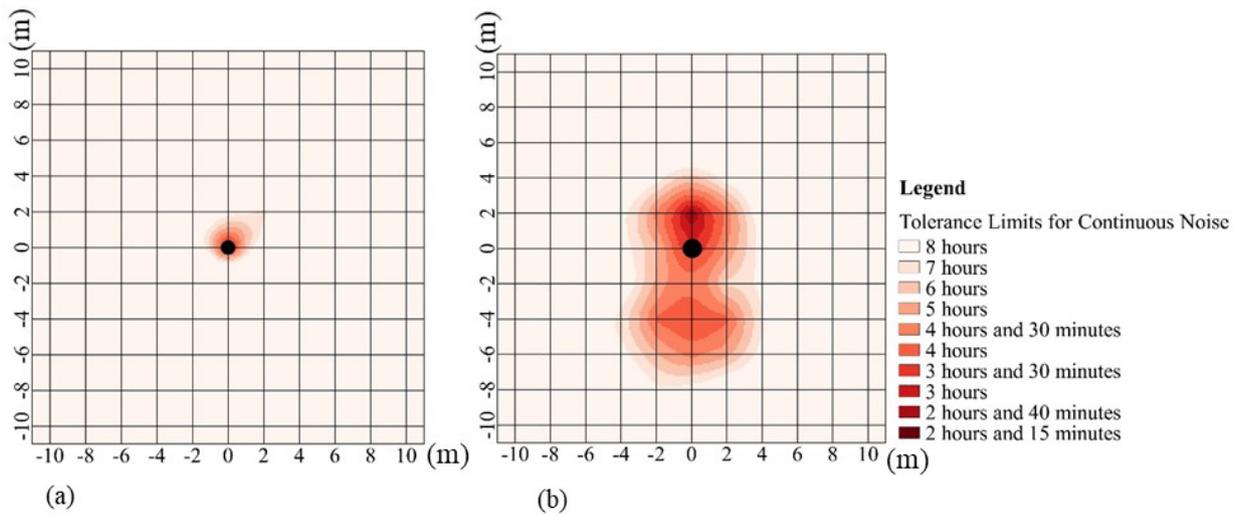
Figure 4. Map of the spatial distribution of the exposure time limits based on the noise emitted by the tractor: a) without rotary cutter activation; b) with rotary cutter activation.
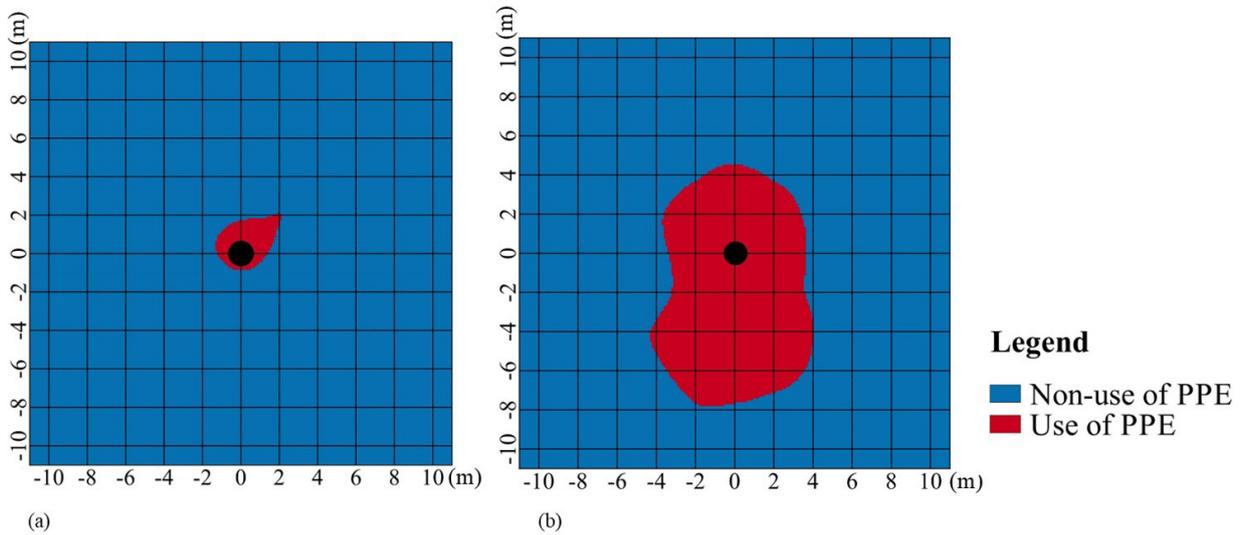

Figure 5. Map of the need for the use or not of PPE. (a) without rotary cutter activation (b) with rotary cutter activation.

CONCLUSIONS

The spatial distribution mapping was created through geostatistical analyses. The wave model was adequate to describe the behavior of this type of data.

The level of noise found in this experiment exceeded the values allowed by Brazilian regulations, with and without the activation of the rotary cutter.

An alternative solution is to limit tractor driving time to less than 3 hours and 30 minutes with the deactivated rotary cutter, and to less than 2 hours and 40 minutes with the activated cutter.

This study helps in the identification of unhealthy areas for the recommendation of hearing protection to agricultural workers. However, it must be emphasized that the use of engineering controls, such as cabin adaption, be considered as a priority control measure, and the use of hearing protection as the last resort. Also, it is recommended that every tractor and its implements be used properly according to the manufacturer's instructions and guidelines.

Acknowledgments

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Conceived and designed the experiments: GASF, LMS. Performed the experiments: LMS. Analyzed the data: LMS, GASF and MLB. Contributed reagents/materials/analysis tools: LMS, GASF, MLB, FBSM and BDSB. Wrote the paper: LMS, GASF, MLB, FBSM and BDSB. All authors read and approved the final manuscript.