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Environmental noise assessment using vegetation indices obtained from satellite imaging

Urban noise affects human health and impacts fauna and flora. Mapping noise levels may contribute to the development of noise mitigation strategies. This paper proposes a noise estimation method for the construction of an acoustic map in urban spaces using satellite images. The method was tested using data from the city of São Luís (MA), Brazil. For one year, noise was measured monthly at 25 points, with different characteristics of noise sources related to types of urban landscapes and rural areas. The month was randomly chosen for data acquisition from the noise monitoring period to estimate an acoustic map using remote sensing data from Landsat 8 satellite and vegetation indices, such as the Normalized Difference Vegetation Index (NDVI). A linear regression model and a second-order polynomial regression function were used to estimate the noise from spectral remote sensing data. The NDVI was the best predictor variable (r2 = 0.8554, p < 0.05) considered to be satisfactory, as the mean square error was 3.8 dB. The tested method and proceedings have been shown to be appropriate for monitoring noise in the city and constructing the acoustic map. Therefore, the results demonstrate a good relation between noise and NDVI allowing to use the regression model to construct acoustic maps using free and easily accessible data, and it has the potential to be used as a tool for planning noise control strategies.

Keywords: Acoustic monitoring; Acoustic mapping; Environmental noise; Satellite imagens.

Avaliação de ruído ambiental usando índices de vegetação obtido de imagens de satélite

O ruído urbano afeta a saúde humana e impacta a fauna e a flora. O mapeamento dos níveis de ruído pode contribuir para o desenvolvimento de estratégias de mitigação de ruído. Este artigo propõe um método de estimativa de ruído para a construção de um mapa acústico em espaços urbanos utilizando imagens de satélite. O método foi testado usando dados da cidade de São Luís (MA), Brasil. Durante um ano, o ruído foi medido mensalmente em 25 pontos, com diferentes características das fontes de ruído relacionadas aos tipos de paisagens urbanas e rurais. O mês foi escolhido aleatoriamente para aquisição de dados do período de monitoramento de ruído para estimar um mapa acústico utilizando dados de sensoriamento remoto do satélite Landsat 8 e índices de vegetação, como o Índice de Vegetação por Diferença Normalizada (NDVI). Um modelo de regressão linear e uma função de regressão polinomial de segunda ordem foram usados para estimar o ruído de dados de sensoriamento remoto espectrais. O NDVI foi a melhor variável preditora (r2 = 0,8554, p < 0,05) considerada satisfatória, pois o erro quadrático médio foi de 3,8 dB. O método e procedimentos testados mostraram-se adequados para monitorar o ruído na cidade e construir o mapa acústico. Portanto, os resultados demonstram uma boa relação entre ruído e NDVI permitindo utilizar o modelo de regressão para construir mapas acústicos utilizando dados livres e de fácil acesso, e tem potencial para ser utilizado como ferramenta para planejamento de estratégias de controle de ruído.

Palavras-chave: Monitoramento acústico; Mapeamento acústico; Ruído ambiental; Imagens de satélite.

Topic: **Geodésia, Cartografia e Sensoriamento Remoto**

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INTRODUCTION

Since 1999 (BERGLUND et al., 1999), the World Health Organization (WHO) has warned that prolonged exposure to environmental noise will continue to progressively affect the global population (YANG et al., 2021). Data show that approximately 10% of the global population is exposed to high noise levels (VAN KEMPEN et al., 2018). Noise pollution is a growing environmental concern and an underestimated threat that can cause a number of short- and long-term health problems, such as those associated with an increased risk of negative physiological and psychological health outcomes (HÄNNINEN et al., 2004; PERIS, 2020). “High noise levels” are defined in the 7th Environment Action Programme - European Commission as noise levels above 55 dB Lden and 50 dB Lnight (BLANES et al., 2017). According to the European Environment Agency report n.° 22/2019 (PERIS, 2020), approximately 40 % of the population is exposed to road traffic noise with an equivalent sound pressure level (SPL) exceeding 55 dB(A) daytime and 20 % are exposed to levels exceeding 65 dB(A). The WHO 2010 defines noise above 65 decibels dB) as noise pollution that is considered dangerous for public health (VIANNA et al., 2015).

Exposure to noise is associated to sleep disorders with awakenings, learning impairment, hypertension ischemic heart disease diastolic blood pressure, reduction of working performance, annoyance (MUZET, 2007; ZACARÍAS et al., 2013; ERICKSON et al., 2017; DRATVA et al., 2012; BABISCH et al., 2005; PETRI et al., 2021; VUKIĆ et al., 2021; ROSSI et al., 2018; MIEDEMA et al., 2001; LICITRA et al., 2016).

Noise pollution is a growing environmental concern (PIRES, 2020; BLANES et al., 2017). Environmental noise is one of the three main causes of illness in humans, along with air and water pollution (SOUZA et al., 2020). The severity of health effects due to noise versus the number of people affected indicates that excessive noise seriously harms human health interferes with people’s daily activities, and acts as a stressor that affects wellbeing. Previous studies indicate that exposure to noise can result in negative impacts on human health, such as daily disruption, discomfort, cognitive impairment, and various issues such as hearing loss, sleep disturbance, cardiovascular diseases, psychophysiological effects, and reduced physical or cognitive performance. Chronic exposure to environmental noise has significant impacts on physical and mental health and wellbeing in child development, such as autism and premature mortality (BABISCH, 2011; AUGER et al., 2018; MUNZEL et al., 2014; LABIB et al., 2019; KUMAR et al., 2009; LEE et al., 2020; KHOSRAVIPOUR et al., 2020; ANDERSON et al., 2020; TEACHER et al., 2020; OKOKON et al., 2018; BLANES et al., 2017).

Environmental noise can be generated by several sources, such as transport (road traffic, rail traffic, air traffic), nightclubs, dwellings, schools and preschools, university campuses, and commercial shopping and traffic areas, including public addresses, indoors and outdoors, and construction industries. The WHO/Europe uses evidence on the health effects of noise to identify the needs of vulnerable groups and offer technical and policy guidance to protect health. A previous report presents an updated assessment of populations exposed to high levels of environmental noise and associated health impacts in Europe based on the new WHO recommendations (KÄLSCH et al., 2014; CHINULA et al., 2017; SOUZA et al., 2020; RABINOWITZ et al., 2006; BLANES et al., 2016; BLANES et al., 2017). The report states that environmental noise, which is caused by various sources but primarily comprises road traffic noise, remains a serious environmental problem affecting the health and wellbeing of the general population.

The Brazilian Association of Technical Norms (Associação Brasileira de Normas Técnicas) established the conditions required for assessing noise in communities. The Brazilian Standard (NBR) Nº 10151/2019 (Acoustics - Measurement and evaluation of SPLs in inhabited environments–Application for general use) recommends measuring the equivalent continuous SPL A-weighted (LAeq) for outdoor settings and reports a range of 35 to 60 dB as suitable for acoustic comfort (MAGIOLI et al., 2018). In addition to national standards, the International Organization for Standardization, ISO 1996-1 (Acoustics – Description, measurement, and assessment of environmental noise–Part 1: Basic quantities and assessment procedures; 2016) and Law N.6287 (12/28/2017) provide a basis for the reduction of noise pollution in the municipality of São Luís. Possible mitigation strategies include setting appropriate noise levels and times during which higher noise levels are permitted, installation of acoustic barriers on roads and highways, creating licenses for sound use, and establishing other provisions (e.g., the Norma Municipal - São Luís - MA, published in the Official Diary of the Municipality (DOM; January 11, 2018). To measure noise, it is necessary to establish measurement parameters, select appropriate equipment, and determine proper calibration, measurement sites, and measurement times (BRÜEL et al., 2000; PÔÇAS et al., 2020).

RS technology provides information about the terrestrial surface, such as topography and vegetation, that support multidisciplinary environmental analyses in urban landscapes. Therefore, representing the terrestrial surface using spectral satellite images is possible owing to the interaction between solar radiation and the terrestrial surface, with different types of land cover absorbing, transmitting, and reflecting solar radiation distinctly at different wavelengths. Thus, several digital image processing techniques are used to extract different information from terrestrial surfaces, which can be used to determine noise levels in urban landscapes (PÔÇAS et al., 2020; MUSHORE et al., 2017; ARAGÃO et al., 2007).

The noise level data can be analyzed using RS techniques with satellite images. Managing urban noise levels involves analyzing the local noise context by constructing environmental noise maps and developing short-, medium-, and long-term strategies according the levels established by existing standards (SMARGIASSI et al., 2021; ANDREASI et al., 2015).

Despite the large number of studies on sound monitoring in outdoor environments, no studies have been conducted using the normalized difference vegetation index (NDVI) derived from remote sensing (RS) data to construct acoustic maps; thus, the vegetation indices (VIs) were created for measurements of vegetation attributes, such as leaf area index, green biomass, productivity and chlorophyll content (MAGIOLI et al., 2018; PÔÇAS et al., 2020; RAVINDER et al., 2014; AGUILER et al., 2015; LABIB et al., 2019).

Therefore, our findings may contribute to ongoing acoustics research and instrument development. NDVI was first reported by Rouse et al. (1973) and has been applied at various scales. It is one of the most commonly used vegetation indices, partially owing to its ease of calculation due to a simple formula that requires only two wavelengths as well as its ability to detect areas covered by vegetation and characterize crop canopies (GOZDOWSKI et al., 2020).

Green spaces have a positive effect on noise pollution, acting as noise buffers. However, their effects have been little explored at the urban level. In addition, the relationship between urban noise, whether industrial noise or noise in means of transport, rural residences, urban or hospitals or schools, commercial and/or administrative, cultural, leisure and tourism activities, green spaces, water bodies, and land cover were investigated in this work, using satellite images. Considering the importance of noise maps, the lack of studies related to environmental data at an urban level, this work aims to develop a novel method of estimating urban noise, compare noise measurements with vegetation indices and obtain a regression model that best fits field data for the construction of acoustic maps (LIU et al., 2021; UEBEL et al., 2021; MARGARITIS et al., 2018; LOPEZ, et al., 2018; YANG et al., 2005; ZHANG et al., 2018).

MATERIALS AND METHODS

Description of the study area

The study area comprises the urban perimeter of the city of São Luís (Figure 1), which is the capital of the State of Maranhão, Brazil (S 2°31', W 44°16'). São Luís comprises approximately 233 neighborhoods, totaling an area of 834.785 km^2 with a population of 1,091,868 inhabitants.

The climate of São Luís is tropical, hot, humid, and strongly influenced by the sea. It exhibits two distinct periods: a rainy period from December to July and a dry period from August to November.

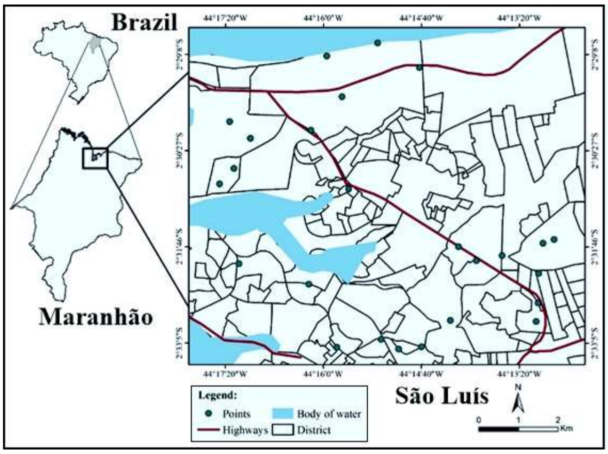

Figure 1: Study site in São Luís, Maranhão, Brazil. Twenty-five sampling points were selected to evaluate the noise levels in different types of areas (green points). For better visualization, only highways were included.

Because it is part of the Amazon biome, the city's vegetation is diverse and exhibits high phytophysiognomic biodiversity. São Luís also has a considerable number of mangroves. The vegetation cover of the municipality is a mixture of hardwood, babassu, dune vegetation, sandbanks, and mangroves. Despite being the capital of the state, São Luís preserves historical heritage characteristics, exhibiting slow horizontal urban development. Therefore, buildings (highly relevant for building reflections) and street canyons (one-sided buildings, etc.) despite scenarios are included, all these have significant little influence on sound propagation in urban areas of São Luis, MA.

Sampling sites 1–25 were selected within the city's urban limits, considering accessibility and representativeness of all existing landscapes, as shown in Table 1.

The simplified evaluation method (NBR N° 10151/2019) was selected for this work because no suspicion of occurrence was observed for sound evaluation due to sources of continuous or intermittent sounds. Therefore, the evaluation was performed comparing the L_{Aeq}, $T_{(total)}$ measured with the contribution of the sounds originating from the sources under evaluation, in the period from May 2017 to April 2018, with the RL_{Aeq} limits according to the use and occupation of the soil in the site measurement study. The result is considered acceptable when it is less than or equal to that established in Table 1.

Sampling points

Table 1 shows the limits of SPLs depending on the types of inhabited areas and the daytime noise levels allowed, according to NBR N° 10.151/2019 for outdoor environments.

Table 1: SPL limits according to type of inhabited area according to NBR N° 10.151/2019 (total sites: 25).

Number of sites/ Measured Points	Types of inhabited areas	% to total sites	Limits in dB RL_{Aeq}* Daytime
01 / 20	Mixed area with predominance of cultural activities, leisure, and tourism	4.0	65.0
10 / 1, 5, 6, 11, 12, 13, 16, and 22	Mixed area, with commercial and administrative activities	40.0	60.0
8 / 2, 3, 4, 7, 17, 19, and 25	Strictly residential urban or hospital or school area	32.0	50.0
4 / 10, 14, 15, and 21	Mixed, predominantly residential area	16.0	55.0
2 / 8, 9, 18, 23, and 24	Rural residences areas	8.0	40.0

* RLAeq denotes the time weighted limit of the sound level in decibels in A-weighting

Methodological approach

Preliminary tests were performed to determine the minimum sampling time necessary for reliable measurements. Measurements were made for 5-, 15-, and 35-min periods at random locations in October 2017.

A-weighted SPLs were measured according to the NBR N° 10.151/2019 standard, always from 11:00 a.m. to 1:00 p.m., including the peak period at noon (12:00 p.m.), under ideal and predicted weather conditions. The city of São Luis has tropical climate conditions with an annual average temperature of 27 °C and wind speed of 2.7 m/s. Measurements were performed using an Instrutherm sound pressure level meter (DEC-6000 model Class 2) that was calibrated and configured for measurements of SPL equivalent in A, with a 95% probability of accuracy according to the technical report of the apparatus. The equipment was fixed at a height of 1.2 m from the ground and at least 2.0 m away from any reflecting surfaces.

Theory/calculation

In this study, images from the Landsat-8 satellite were used, acquired for free from the United States Geological Survey website on October 5, 2017 (orbit/point: 220/062). The spatial resolution of the image was 30 m. The Landsat-8 satellite is part of an Earth observation program developed by the National Aeronautics and Space Administration (BOORI et al., 2015). The date of acquisition of the satellite images was selected without cloud cover with less and less uniform cloud cover.

A linear regression model and a second-order polynomial regression function were used to estimate the noise from spectral RS data. Linear regression models are widely used to estimate spectral responses (ZHANG et al., 2019). Noise measurements at 25 points (Figure 1) of L_{Aeq} were taken, and noise monitoring data was taken in October 2017 (Figure 2) and compared with RS data to investigate correlations.

The biophysical principle and morphology of vegetation behind the relationship between noise intensity and spectral data (near infrared and red), using digital data from Landsat 8 lies in the probability of major noise intensity occurring in open urban areas, without vegetation, and with large roads and high concentrations of people (ZHANG et al., 2013).

From the processed image, it is possible to identify vegetation-covered regions and calculate vegetation indices, such as the EVI, NDVI, normalized difference moisture index (NDMI), modified soil-adjusted vegetation index, and soil adjusted vegetation index. NDVI is the most commonly used method in RS (GITELSON et al., 2012). Rouse et al. (1974) developed the NDVI, represented by Equation 1:

$$\mathrm{NDVI} = \frac{\mathrm{P_{nir}} - \mathrm{P_{red}}}{\mathrm{P_{nir}} + \mathrm{P_{red}}} \qquad (1)$$

where P_{nir} and P_{red} are the bands in the infrared and red regions, respectively. NDVI ranges between –1 and +1, between –1 and near zero in areas without vegetation, and above zero in areas with a high possibility of vegetation (ZHANG et al., 2013).

The EVI was created for Moderate Resolution Imaging Spectroradiometer (MODIS) sensor data, according to Equation 3:

$$EVI = G\frac{P_{nir} - P_{red}}{P_{nir} + C_1P_{red} + C_2P_{blue} + L} \qquad (3)$$

where G is the gain factor quantified at 2.5; C1 and C2 represent coefficients of the blue to red band considering the atmospheric scattering by aerosols determined empirically with values of 6,0 and 7,5, respectively; and L is the empirical solids factor of 1.0 (ZHANG et al., 2014).

To validate the model, 5 points (4, 14, 16, 19 and, 25; Table 2) were randomly selected among the 25 sampling sites, and the root mean square error (RMSE), expressed in Equation 2, was employed to compare predicted and measured values.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \qquad (2)$$

where y_i is the measured value, $\hat{y}_i$ is the predicted value for the *i*-th measured sample, and n is the number of points used for model validation.

For the construction of the acoustic map of the study area, the data measured in the described points and vegetation indices, the ENVI 5.0 software will be used to generate the proposed methodology using the linear regression equation.

Datasets were first tested for normality using the Shapiro–Wilk and Kolmogorov–Smirnov tests. Analysis of variance (ANOVA), the Brown–Forsythe test, and Bartlett’s test were performed to group the sampling points according to the noise magnitude to a 5% ($\alpha = 0.05$) significance level, thus determining statistically equal points in terms of the SPL.

RESULTS AND DISCUSSION

Analysis of urban noise

Figure 2 shows the averages of measured data at all monitoring sites over a year. Measurements were made for 5-, 15-, and 35-min periods. The coefficient of variation was below 10% for all points, showing little noise variation at these sites during the period of observation (from May 2017 to April 2018) between 11:00 a.m. and 1:00 p.m., including the peak period at 12:00 p.m.

All points are above the Norm allowed, by comparing L_{Aeq} (depending on the types of inhabited areas and the daytime noise levels allowed for outdoor environments), except for points 8 and 9, which lie inside an environmental reserve with dense vegetation.

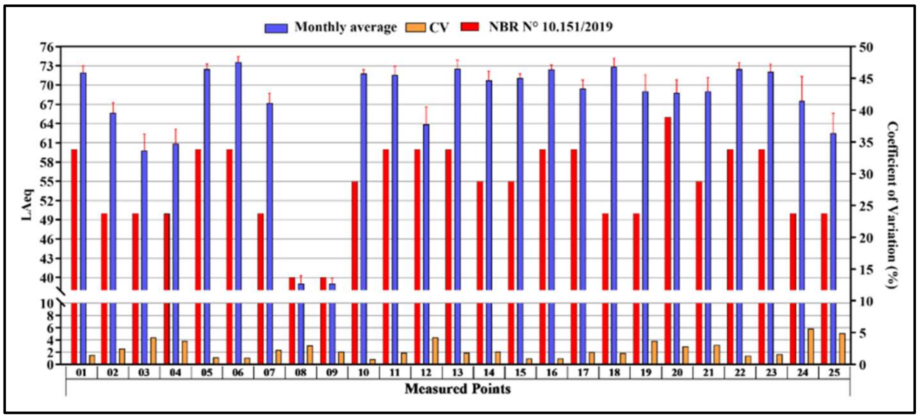

Figure 2: Monthly averages of the monitoring period of SPL A-weighted and coefficient of variation of all points. L_{Aeq} denotes the time-weighted average of the sound level in decibels in A-weighting. Those by the same letter did not differ from each other at a significance level of 5 %; CV 0.9 %.

Figure 2 shows the monthly averages considering all periods and locations of the noise monitoring points. Using nonparametric tests (one-way ANOVA), significant differences were observed between measurement groups at all monitoring points (F = 626.100; p-value < 0,0001; R square = 0.9901).

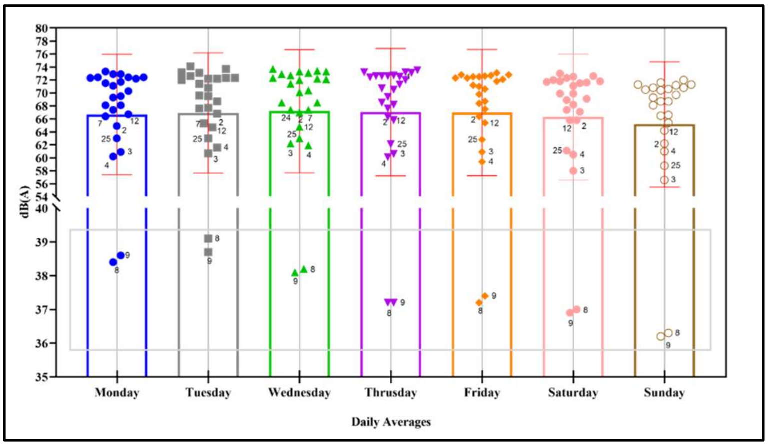

Figure 3: Averages by weekday of A-weighted SPL.

Figure 3 shows averages per weekday, considering all measurement periods. SPL values tend to decrease along the week, while CV values tend to increase, varying between 10% and 15%. Higher CVs occur on the weekend, reflecting the greater freedom from schedules people enjoy during those days.

The monthly average of each weekday was assessed throughout the acoustic monitoring period. Several significant differences were observed between the groups (p << 0.001). L_{Aeq} values for Saturday and Sunday indicated no significant difference (values between 56.6 to 65.8 dB for Points 2, 3, 4, 7, 12, and 25), and the same was observed for Tuesday to Friday (values between 59.4 and 66.7 dB for the same points). For all days of the week, Points 8 and 9 showed values between 36.2 and 39.1 dB, as shown in Figure 3.

Figure 3 shows that 92% of the sound level values are higher than 55 dB (A), an acceptable limit for the region under study, according to NBR N. 10.151 / 2019 and Law N. 6287 of 12/28/2017.

These results show that São Luís exhibited differences between the monitored areas (urban, rural, and mixed areas, according to the NBR N° 10.151/2019) throughout one year with constant urban noise of heterogeneous sources (traffic, rail, aircraft, construction, etc.) on all days of the week.

Acoustic map generation

Figure 4 presents the spread of the results showing the mean ± standard deviation and median values of sound pressure measurements for 5-, 15-, and 35-min periods (n = 60, 180, and 420, respectively). To compare measurements at each location, statistical tests were performed. For this, datasets were first tested for normality using the Shapiro–Wilk test (p-value > 0.05) and Kolmogorov–Smirnov test (p-value > 0.1000); in all cases, the data followed a normal distribution. LAeq values for Saturday and Sunday show no statistical difference. The same is true for the Tuesday to Friday period.

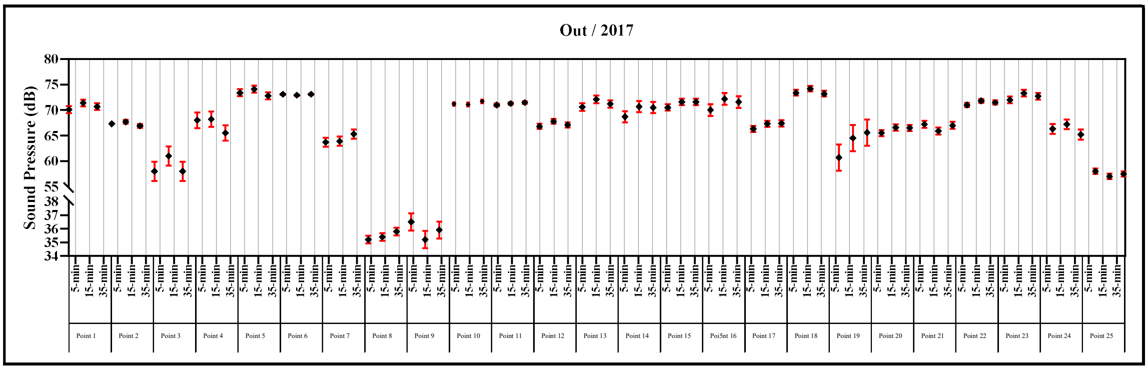

Figure 4: Mean (◆) ± standard deviation and median values of sound pressure measurements considering 5 (n = 60), 15 (n = 180) and 35 min (n = 420) periods.

For parametric tests, one-way ANOVA was used to compare three groups (5-, 15-, and 35-min periods). No significant differences were observed between measurement groups at all points monitored (p-value > 0.05; F = 0.032; p-value = 0.9703). Therefore, the results indicate that the 5-, 15-, and 35-min measurements are adequate to indicate the sound pressure at different locations; thus, the results considered the average value of the three measurements. The coefficient of variation (CV) was calculated using the monthly average of $L_{Aeq.}$

The vegetation index data, presented from the NDVI calculation, are highlighted in Figure 5. As already highlighted, the data that represent the vegetation are green (values greater than 1). Linear Spectral Mixture Model data extracted from satellite Landsat 8 image, according to Table 2.

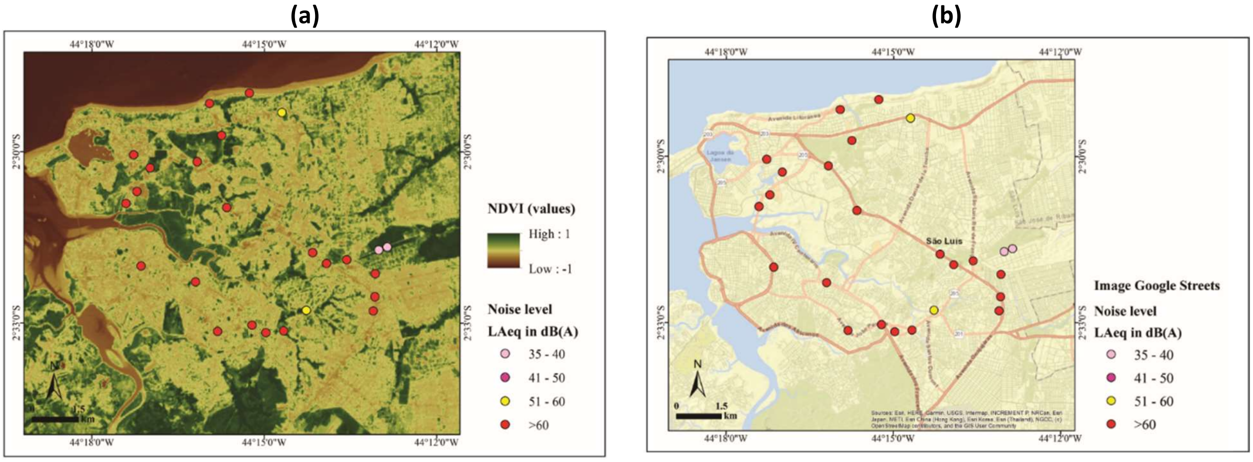

Figure 5: (a) NDVI values and noise level LAeq (points) in dB(A) map of the study area and, **(b)** Google Street image (available on the internet and free of charge) and points of locations to better observe places and streets in the municipality of São Luís, MA.

Table 2: Imagens from the Landsat 8 satellites, utilized NDVI.

Points	LAT	LONG	NDVI
1	-2,529408	-44,236039	0,14305922
2	-2,532586	-44,231964	0,24698299
3	-2,546236	-44,237867	0,15922530
4	-2,546444	-44,218403	0,10747946
5	-2,542239	-44,217956	0,11140841
6	-2,531453	-44,226142	0,04762277
7	-2,535511	-44,217842	0,14450362
8	-2,528606	-44,216872	0,36260942
9	-2,527731	-44,214378	0,44833398
10	-2,552361	-44,263586	0,12542763
11	-2,533325	-44,285806	0,04787769
12	-2,511578	-44,286978	0,20493127
13	-2,537972	-44,269989	0,03096009
14	-2,515106	-44,290203	0,06884708
15	-2,550569	-44,253564	0,11530595
16	-2,552225	-44,244422	0,28004703
17	-2,552775	-44,249589	0,16939978
18	-2,502867	-44,269506	0,24505129
19	-2,495200	-44,262469	0,39221802
20	-2,482908	-44,254392	0,14080600
21	-2,485906	-44,265936	0,13834959
22	-2,516267	-44,260939	0,07055058
23	-2,500886	-44,287939	0,08785558
24	-2,504706	-44,283217	0,45133236
25	-2,488500	-44,244914	0,10454227

A linear regression model and a second-order polynomial regression function were generated from the spectral data obtained from such L_{Aeq} measurements.

Figure 6 shows the calibration curve of the current situation, measured in October 2017, using RS to estimate the noise map. Through the generated regression model, we can estimate the noise value through vegetation indexes.

The vegetation indices that best correlated with the L_{Aeq} noise levels were NDVI, presenting a coefficient of determination $r^2 = 0.8554$ (EVI; $r^2 = 0.5836$; $p < 0.05$), and a second-order polynomial regression function equal to $r^2 = 0.9188$ (EVI; $r^2 = 0.9324$; $p < 0.05$). The EVI was not the best predictor variable ($r^2 = 0.5836$, $p < 0.05$) considered to be satisfactory, as the mean square error was 4.8 dB (Figure and Table and not included).

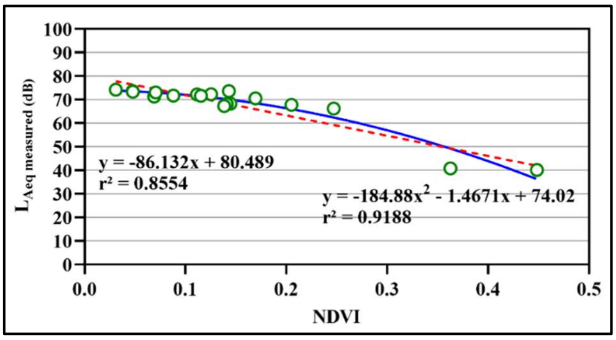

Figure 6: Calibration curve of the simulations. The indexes that best correlated with the L_{Aeq} noise levels were NDVI. The lines show a linear regression function (dah-dotted) and a second order polynomial regression function (dashed). The linear regression equation was expressed as follows: $y = -86.132x + 80.489$ with a correlation coefficient of 0.8554.

The results of the linear regression analysis and a second-order polynomial regression function (Table 3) show that the model presents significant results with $p < 0.05$. Table 4 shows the significance test F, which demonstrates the rejection of the null hypothesis and ensures that the model can estimate the noise levels in the tested variable.

Table 3: Results of linear regression analysis and a second order polynomial regression function.

Regression Statistics	
	NDVI
Multiple R	0.9248
R-squared	0.8554
Adjusted R-square	0.8463
Standard error	0.0427
Observations	18

The analysis of the model by the significance test F demonstrates the rejection of the null hypothesis and guarantees that the model can estimate the noise levels in the tested variable, as the calculated F (Table 4) exceeds the tabulated value (F for $p < 0.05$ equals 4.54).

Table 4: Linear model variance analysis.

NDVI x Noise	***Df***	***SS***	***MS***	***F***	**Significance *F***
Regression	1	0.1731	0.1731	94.6562	4.0194×10^{-8}
Residual	16	0.0292	0.0018		
Total	17	0.2024			

The linear regression model used to estimate the noise presented an average square error of 3.8 dB, which was considered acceptable according to the value established by the European Commission Working Group Assessment of Exposure to Noise for noise maps in urban areas, that is, ± 4.0 [uncertainty in dB(A)]. In a study conducted by Guedes et al. (2014), the error found between simulated and measured noise levels reached + 4.7 dB(A); this was also considered acceptable according to the same reference (BOORI et al., 2015; MANVELL et al., 2011; MURPHY et al., 2010; GUEDES et al., 2014).

Law No. 6287 establishes 70 dB(A) set as the daytime limit. Is set as the maximum sound level for residential, commercial, service, institutional, industrial, special, religious, public, or private undertakings or activities as well as from motor vehicles at any point. This law considers daytime to be from 7 am to 6 pm.

Applying the proposed methodology: Acoustic map development

After testing and validating the regression model, we constructed an acoustic map (Figure 7) using the data measured in the described points and the vegetation indices (Figure 5).

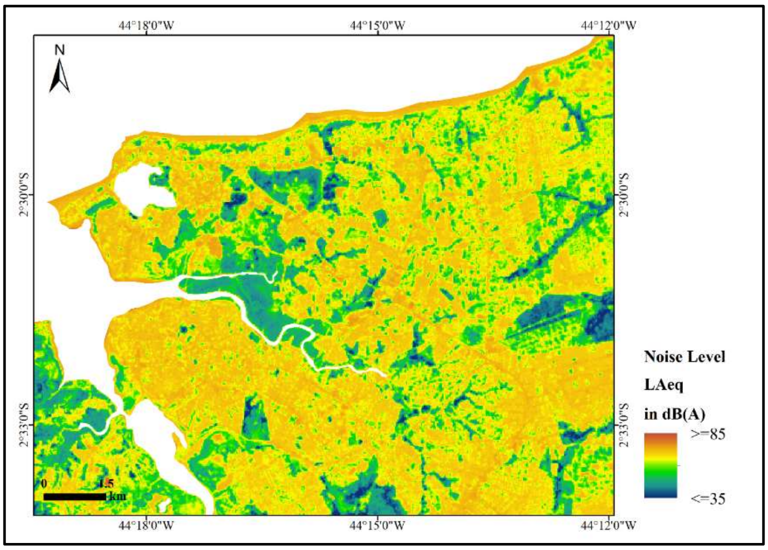

Figure 7: Acoustic map of São Luís (MA) using RS processed via NDVI images. Median values of sound pressure measurements considering 5 (n = 60), 15 (n = 180) and 35 min (n = 420) periods, according to Figure 4. The gradient colours do help to understand there is a spatial relationship of the sound levels to the noise sources present in the area, in comparison of Figure 4 (points).

The highest sound level values were recorded in high-flow urban roads, characterized in the map from orange to red (Figure 7). The regions of the map in blue to green are where the lowest noise values were found; the blue color characterizes regions with denser vegetation where the noise levels are attenuated.

The sound levels observed on the margins of the main venues (not shown in Figure 7) become even more worrying when comparing them with those established by the WHO, in which noise levels from 70 dB(A) can cause diseases depending on the time of exposure and the susceptibility of each individual.

From Figure 7, it is possible to observe the attenuation of sound pressure with the increase of the distance in relation to the main avenues and streets, and due to the presence of common obstacles, such as walls and buildings). In the points furthest from the avenues and in the center of the square, squares, areas of low and dense vegetation and mangroves, the sound levels assume lower values, indicating the lesser noise impact of urban traffic in these places.

CONCLUSIONS

According to the work data, it is concluded that the linear regression model correlating noise levels with vegetation indices presented $r^2 = 0.8554$ for $p < 0.05$. This is satisfactory as the mean square error was 3.8 dB(A). Therefore, it is possible to estimate the noise levels using a georeferenced satellite image for any time of the year from the vegetation index, implying that the proposed method is effective.

The map shows the great importance of vegetation to the population and that deforestation is harmful in all senses, including the increase in noise levels. It is verified that all deforested regions contribute directly to increased noise pollution. Therefore, preserving the existing vegetation is important, as it is a natural source of noise attenuation.

This instrument is useful because in some countries, such as Brazil, data on noise maps and action plans in public management are still lacking. Given the negative impacts on human health and the large number of people affected, environmental noise is therefore a significant concern for citizens and for public policies in cities in public and/or rural areas. Thus, it can be concluded that noise maps play a fundamental role in city planning because exposure to high levels of noise is harmful to human health.

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