REVISTA DE CIÊNCIASAGRÁRIAS
Amazonian Journal
of Agricultural and Environmental Sciences
www.ajaes.ufra.edu.br

ORIGINAL ARTICLE

Use of the linear spectral mixture model in the Saracá-Taquera National Forest

Uso do modelo linear de mistura espectral na Floresta Nacional Saracá-Taquera

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KEYWORDS
Fraction-image
Forage index spectral index
Landsat 8
Remote sense

PALAVRAS-CHAVE
Imagem-fração
Índice espectral de degradação florestal
Landsat 8
Sensoriamento remoto

ASSOCIATE EDITOR
Thiago de Paula Protásio

ABSTRACT: The Saracá-Taquera Conservation Unit is one of the most exuberant National Forests, rich in biodiversity and with a high potential for the use of natural resources. The objective of this study was to identify signs from forest exploiting and activities with potential for degradation in the Saracá-Taquera National Forest (FLONA-ST), using the linear spectral mixture model (LSMM) in an image recorded in 2020. The study was carried out at FLONA-ST, located in the mesoregion of the Lower Amazon. The images were acquired with the Geological Service of the United States. The collected scenes, 228/061 and 229/061, were submitted to compositions of bands 6, 5, and 4 of Landsat 8, mosaic, and the image clipping corresponding to the area of FLONA. The LSMM was applied and the Spectral Index of Forest Degradation (DEGRADI) was determined. Then, the technique of slicing and vectoring of images was applied, for further classification based on visual interpretation. The use of LSMM and DEGRADI were able to identify the deforested areas in FLONA-ST. In general, FLONA was predominant in areas covered with dense and heterogeneous vegetation. However, areas with exposed soil were observed in the central, north, northeast, southeast, and south parts, whether intended for mining, agricultural activities, housing, or for the exploitation of forest resources in FLONA. The forest exploitation in FLONA was observed, mostly, within the Forest Management Units, where exploration caused by disordered and geometric selective logging was found.

RESUMO: *A unidade de conservação Saracá-Taquera está entre as Florestas Nacionais mais exuberantes, com alta biodiversidade e potencial de uso dos recursos naturais. O objetivo desse estudo foi identificar as cicatrizes de exploração florestal e as atividades com potencial de degradação na Floresta Nacional de Saracá-Taquera (FLONA-ST), com o uso do modelo linear de mistura espectral (MLME) em imagem registrada no ano de 2020. O estudo foi realizado na FLONA-ST, localizado na mesorregião do Baixo Amazonas. A aquisição das imagens foi feita junto ao Serviço Geológico dos Estados Unidos. As cenas coletadas, 228/061 e 229/061, foram submetidas a composições das bandas 6, 5 e 4 do Landsat 8, mosaico e o recorte da imagem correspondente a área da FLONA. Foi aplicado o MLME e determinado o Índice Espectral de Degradação Florestal (DEGRADI). Em seguida, foi aplicada a técnica de fatiamento e vetorização de imagens, para posterior classificação com base na interpretação visual. O uso do MLME e do DEGRADI foram adequados para identificar as áreas desmatadas na FLONA-ST. De maneira geral, a FLONA apresentou predominância em áreas cobertas com vegetação densa e heterogênea. No entanto, áreas com solo exposto foram observadas nas porções central, norte, nordeste, sudeste e sul, seja destinada a mineração, atividades agropecuárias, habitação ou para exploração dos recursos florestais da FLONA. A exploração florestal na FLONA foi observada, em sua maioria, dentro das Unidades de Manejo Florestal, sendo detectado exploração por corte seletivo desordenado e geométrico.*

Received: 30/03/2021
Accepted: 30/10/2021

1 Introduction

According to Art. 225 of the Federal Constitution of 1988 (Brasil, 1988): “everyone has the right to an ecologically balanced environment, a common good for the people and essential to a healthy quality of life, imposing itself on the Public Power and on the community the duty to defend it and preserve it for present and future generations”. Although this right was provided at the top of the Brazilian legal system, there are many doubts about the quality of the environment in the future (Matos *et al.*, 2018).

Currently, much is discussed on climate change, air pollution, deforestation, species extinction, land degradation and researchers around the world have warned of the consequences that these environmental problems can have on the planet's ability to sustain life, therefore, a great threat to human existence (Oliveira *et al.*, 2020).

In the last years, deforestation in the Amazon has been advancing at an accelerated pace, partly due to the lack of awareness of individuals and companies that use the forest resources, but also due to the lack of more effective actions for forest protection and conservation, on behalf of the government.

Data from the National Institute for Space Research (INPE) revealed that by July 2019, approximately 17% of the Amazon Forest (719,014 km²) had been deforested (Miranda *et al.*, 2020). Only in 2019, deforestation of 9,165.6 km² of the Amazon forest was registered (Silva, 2020). This deforestation has even advanced over the specially protected areas established in Article III, 1st paragraph of the CF/88, such as the Conservation Units (CU).

According to Duarte et al. (2020) it is necessary to observe deforestation in a specific way for each region, as it can occur through predatory and illegal exploration or with Sustainable Forest Management, with the use of concepts related to Exploration with Reduced Impact (ERI). The main pressures for legal or illegal deforestation to occur are related to logging, expansion of agricultural activities, increase in population density, tax incentives, proximity to roads and mineral extraction areas (Barber *et al.*, 2014; Fearnside, 2017; Sonter *et al.*, 2017; Curtis *et al.*, 2018).

According to INPE (2021) the Saracá-Taquera National Forest (FLONA-ST), in the period between 2008 and 2020, had 53.06 km2 of deforested area, a fact that occurs throughout Pará, when analyzing the period from 1988 to 2020, it can be seen that the state is the main responsible for the deforestation of the Amazon forest, with an area of deforestation recorded in 157,374 km² and a representation rate of 34.42% (INPE, 2021). Among its main causes, one can mention the low level of implementation of the management plan, which makes these areas vulnerable to illegal occupation, predatory exploitation of wood and land, and legal actions for the reduction of the size or degree of protection of the CU's (Araújo *et al.*, 2017). According to Araújo *et al.* (2017), FLONA-ST, is among the 50 most deforested areas in the region, contradicting the role of a conservation unit.

In order to reduce the pressure on forest areas, the Brazilian Forest Service (SFB) issued concessions through the Annual Forestry Grant Plan for selective exploration in some Conservation Units, a fact that authorizes National Forests to receive Forest Exploitation projects with Reduced Impact (BRASIL, 2016).

FLONA-ST, which was created by Decree number 98,704 of December 27, 1989, published in the D.O.U. of 12/27/89 (Brazil, 2000), is a Federal Conservation Unit for sustainable use located in the State of Pará with 429,600 ha of extension. The forest's biodiversity is among the most exuberant ever found, also presenting high levels of fauna and flora diversity. It has great potential for forest resources, timber, and non-timber, mineral potential with the mining of bauxite, and a source of refuge for the biological conservation of wild fauna intact. These facts, associated with the environmental characteristics, transform the area into a CU of paramount importance in the protection and conservation of the Amazon biome (STCP, 2001).

Environmental monitoring is a decisive strategy to ensure the perpetuity of the natural resources in the CUs, and in turn, the application of remote sensing techniques to assess and monitor the health of the CUs are viable alternatives that are already being practiced by several government and non-government institutions for the inspection of protected areas. These techniques include digital image processing (DIP), aiming to qualitatively and quantitatively estimate changes in vegetation cover caused by natural or anthropogenic factors. Among the techniques that can be applied to detect the changes, it can be mentioned the transformation of orbital images into the so-called fraction images is based on the application of the Linear Spectral Mixture Model (LSMM) (Shimabukuro *et al.*, 1998).

LSMM is widely used to identify signs from forest fires as well as stockyards, skid trails, and tree fall clearings, which are the main features of selective logging (Shimabukuro & Smith, 1991). In practice, the model estimates the abundance of water/shadow, bare soil, and photosynthetically active vegetation within each pixel using the spectral signatures of prototypical training areas denominated “endmembers” or “pure pixels” (Pinheiro *et al.*, 2016). The images obtained using this technique are less subject to variations in factors, such as lighting conditions in the scene and atmospheric variations when compared to vegetation indices (Shimabukuro *et al.*, 1998).

Thus, the objective of this study was to identify the scars of forest exploitation and other activities with potential degradation in FLONA-ST using a linear model of the spectral mixture.

2 Materials and Methods

2.1. Record of Forest Exploitation

In December 1989, the Executive Branch, through Decree 98,704, created the Saracá-Taquera National Forest (FLONA-ST), with an estimated area of 429,600 hectares, integrated into the structure of the Brazilian Environmental Institute and Renewable Natural Resources (IBAMA). However, since 1976, a legalized mining activity has been performed in the locality.

According to Nepomuceno (2017), this FLONA-ST is characterized by three sociological variables that reside in the area, as follows: traditional riverside communities, non-traditional communities, and riverside communities that remain from quilombos. In addition to the environmental pressure caused by the residential occupation, mining (De Paiva Salomão *et al.*, 2020) is the major degrading activity recorded in the area. Mineração Rio do Norte has been operating in the region since the late 1970s (Reis, 2006).

FLONA-ST has losses resulting from vegetation burning processes, which is an incidence that has increased as a result of soil tillage for agricultural activities generated by rural producers, as they work with cutting and burn management (Filho *et al.*, 2019).

According to Almeida (2018), it is important to highlight that the area released by the Brazilian Forest Service for the practice of Sustainable Forest Management has a forest production zone of 154,742.98 ha. It is noteworthy the fact that with the growth of the area for the exploitation of resources, deforestation has raised due to the construction of roads for the displacement of workers in the region (Diniz *et al.*, 2009).

2.2. Area characterization

The study was carried out in the Federal Conservation Unit denominated FLONA-ST, whose territorial limit covers part of the municipalities of Oriximiná, Faro, and Terra Santa, both located in the mesoregion of the Lower Amazon, northwestern Pará State (Figure 1). This FLONA covers a protection area of 441,282.63 ha of the Amazon Biome. The factors that most impact the region are: legal bauxite extraction within FLONA; illegal deforestation; siltation and damming of streams; suppression of riparian forest by local riverside dwellers (Bevilacqua *et al.*, 2020).

According to Vieira Júnior (2016), FLONA-ST has four distinct geomorphological units (plateau tops, slopes, lowlands, and alluvial surfaces). The altimetric variations in the area range from areas with altitudes of less than 20 m to areas with altitudes of 190 m. The areas with the highest altitudes (top of plateaus and slopes) are concentrated mainly in the central and northwestern regions of FLONA-ST. The areas with lower altitudes (lowlands and alluvial surfaces), on the other hand, are located mainly in peripheral areas, entering towards the center because of the drainage channels (Figure 1).

FLONA-ST is bathed by the Trombetas and Nhamundá river basins with a great abundance of lakes, which in turn are inserted in the great Hydrographic System of the Amazon River (STCP, 2001). The predominant soils in the region are: Gleysols, on alluvial surfaces; Neosols, found in lowlands; and Argisol and Oxisols, occupying the slopes and tops of the plateaus (Vieira Júnior, 2016). Regarding vegetation, the following vegetation formations predominate: Dense Ombrophilous Forest, Pioneer Formations with Fluvial Influence, and Campinarana (Reis, 2006).

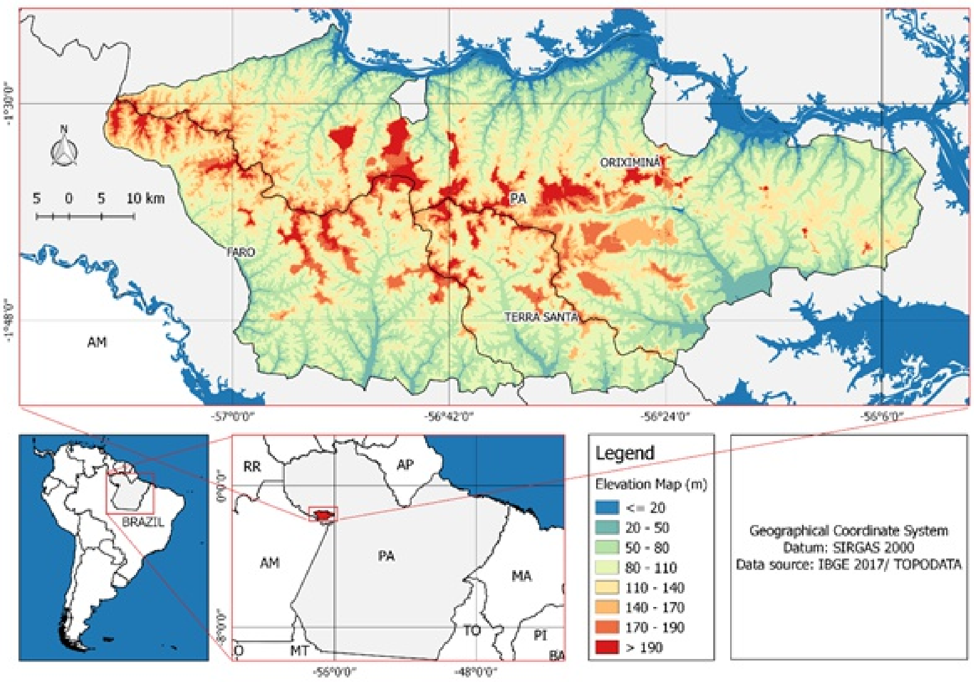

Figure 1. Saraca-Taquera National Forest location map (Source: TOPODATA; IBGE 2017).

Figura 1. Mapa de localização da Floresta Nacional de Saraca-Taquera (Fonte: TOPODATA; IBGE 2017).

The climate is of the Aw type (Koppen's classification), with maximum and minimum temperatures of 31 and 22.5°C, respectively, and an annual average of 25.6°C. The relative humidity of the air is greater than 80% (Vieira Júnior, 2016). Rainfall approaches 2,000 mm annually, with irregular distribution throughout the year (STCP, 2001). According to the National Institute of Meteorology (INMET) record of the last eight years (2012-2020) obtained from the Óbidos A232 meteorological station, the rainy season starts in December and ends in May, in which March is the rainiest month. The less rainy season starts in July, extending until October, in which September is the month with the lowest rainfall volume (Figure 2).

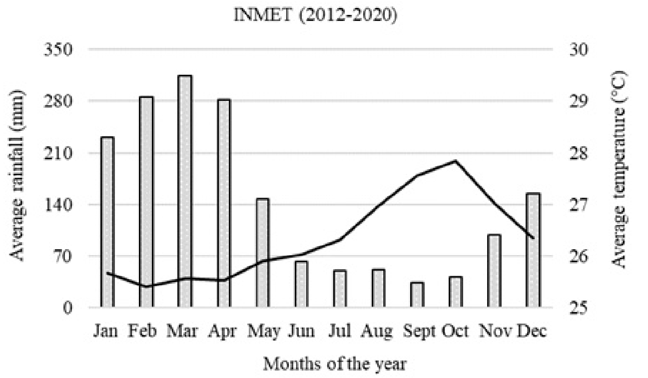

Figure 2. Monthly averages of precipitation and temperature obtained at the Óbidos A232 weather station, located in the Lower Amazon region (Source: INMET, 2020).

Figura 2. Médias mensais de precipitação e temperatura obtidas na estação meteorológica Óbidos A232, localizada na região do Baixo Amazonas (Fonte: INMET, 2020).

2.3. Acquisition and pre-processing of images

For the development of the research, orbital images were acquired (orbit/point 228/061 and 229/061) from the Landsat 8 satellite (OLI sensor) recorded in the second period of 2020. The images, in Geotiff format, were obtained from the United States Geological Servey – USGS database. The spatial and temporal resolution of the sensor is 30 m and 16 days, respectively. It is noteworthy that the Landsat 8 images were made available by the USGS with geometric, atmospheric, and radiometric correction.

As a way of standardizing the images obtained, as well as to ensure the greater distinction between the phyto-physiognomies and less interference from seasonality (phenology), the images were selected in the less rainy period, recorded in the period from July to October, giving preference to images with up to 10% of cloud cover.

Concomitant with the acquisition of orbital images (raster), vector data in Shapefile format were acquired from the territorial limit of the Saracá-Taquera Forest, of the municipal and state limits of the territory of Pará from the IBGE Map Portal.

With the aid of TerraAmazon Software, version 4.5.1, image composition was performed using bands 4 (λ=0.64-0.67 µm - red), 5 (λ=0.85-0.88 µm - near-infrared, green) and 6 (λ=1.57-1.65 µm - shortwave infrared, blue), from Landsat 8 (OLI). Then, a mosaic of the scenes was made and, later, the clipping of the area of interest (FLONA Saracá-Taquera) using the territorial limit of the respective PA as a mask.

2.4. Linear Spectral Mixture Model (LSMM)

The composite image was decomposed into fractions of three basic components (soil, vegetation, and shade/water) using the Linear Spectral Mixture Model (LSMM) made directly using the TerraAmazon software, version 4.5.1, with the aid of the Digital Image Processing Plugin "Terra Image". According to Shimabukuro & Smith (1991), the LSMM estimates the abundance of shadow/water, exposed soil, and photosynthetically active vegetation within each pixel based on the spectral signatures of prototypical training areas denominated "endmembers" or "pure pixels" (Shimabukuro & Smith, 1991; Pinheiro *et al.*, 2016). The linear spectral mixture model can be represented by equation 1:

$$r_i = a\ veg_i + b\ soil_i + c\ shadow_i + e_i \qquad \text{Equation 1}$$

where: ri is the spectral response of the pixel in band i; a, b and c are the proportions of vegetation, soil, and shadow (or water); vegi, soili, and shadowi are the spectral responses of the vegetation, soil, and shadow components; and ei, the error in band i, where the subscript i is the considered band (Viçoso, 2018).

Pure pixels or endmembers used as input data for the application of the model were selected directly in the composite image through the selection of pixels with the spectral response closest to the theoretical curve expected for pure targets (Shimabukuro & Smith, 1991; Anderson *et al.*, 2005). An independent model was generated for each fraction.

2.5. Spectral Index of Forest Degradation (DEGRADI)

To increase the enhancement of the elements indicating forest exploitation, the DEGRADI was calculated using the images fraction soil and vegetation, obtained with the application of the LSMM. This index has been used to improve the detection of forest degradation in Amazon monitoring systems (INPE, 2008) and is based on the assumption that the high spectral contrast between soil and vegetation fractions highlights the major characteristics of selective logging and forest fires (Pinheiro *et al.*, 2016). The DEGRADI Index was calculated according to equation 2:

$$DEGRADI\ = G\ x\ \frac{IFS}{IFV} + \text{Off} \qquad \text{Equation 2}$$

where DEGRADI is the Forest Degradation Spectral Index; G is the gain (multiplication factor, generally used to highlight spectral differences between images); IFS is the solo fraction image; IFV is the vegetation fraction image and; o Off is the offset (additive factor, generally used to highlight similarities between different bands or images). According to Pinheiros et al. (2016), gain and offset values were empirically and interactively applied to each image to highlight the features of interest.

2.6. Level slicing and image vectoring

From the image generated using the DEGRADI Index, the level slicing technique was applied to highlight the pixels whose intensities lie within specific intervals, defined by means of visual analysis. The slicing of intensity levels represents the simplest form of classification besides being applied to a single spectral band at a time (CROSTA, 1999). Then, the vectorization of the sliced areas was carried out for further classification using as a basis the visual interpretation (NOVO, 2008), the CU management plan (STCP, 2001), and high-resolution images recorded in the study region, available free of charge on the online platform Google Earth by the company Google. Thus, the vectored areas were separated into four classes (mining areas, deforestation, urban occupation, and forest management area), considering the minimum size of 6.25 ha, according to the Methodology used in the PRODES and DETER Projects (Souza *et al.*, 2019).

Once all the image processing was completed, the measurement of the vectorized areas (ha) corresponding to each identified class was carried out, with the aid of the field calculator, available in the QGIS 2.18 software. Then, the vector images, in shapefile format, were gathered in a single image for generating and exporting maps in "tif" format.

3 Results and Discussion

Preliminary visual analysis of the 456 false-color composite image of the Saracá-Taquera National Forest (FLONA-ST) allowed us to observe that most of the CU is covered by dense and heterogeneous vegetation (Figure 3A), where forest cover of native species should predominate as recommended by Law No. 9,985/2000 in its Article 7th. Despite this, there is evidence of anthropic activities in the CU that can be of a legal or even illegal nature.

The presence of legal anthropogenic activity within the CU is justified by its basic objective of creation: "the sustainable multiple use of forest resources and scientific research, with an emphasis on methods for the sustainable exploitation of native forests". Thus, traditional populations that lived on the local before the decree of creation of the CU, as well as mining and forest management activities carried out by companies licensed by the Brazilian Institute of Environment and Natural Resources (IBAMA) are authorized to maintain their activities in a sustainable way (STCP, 2001).

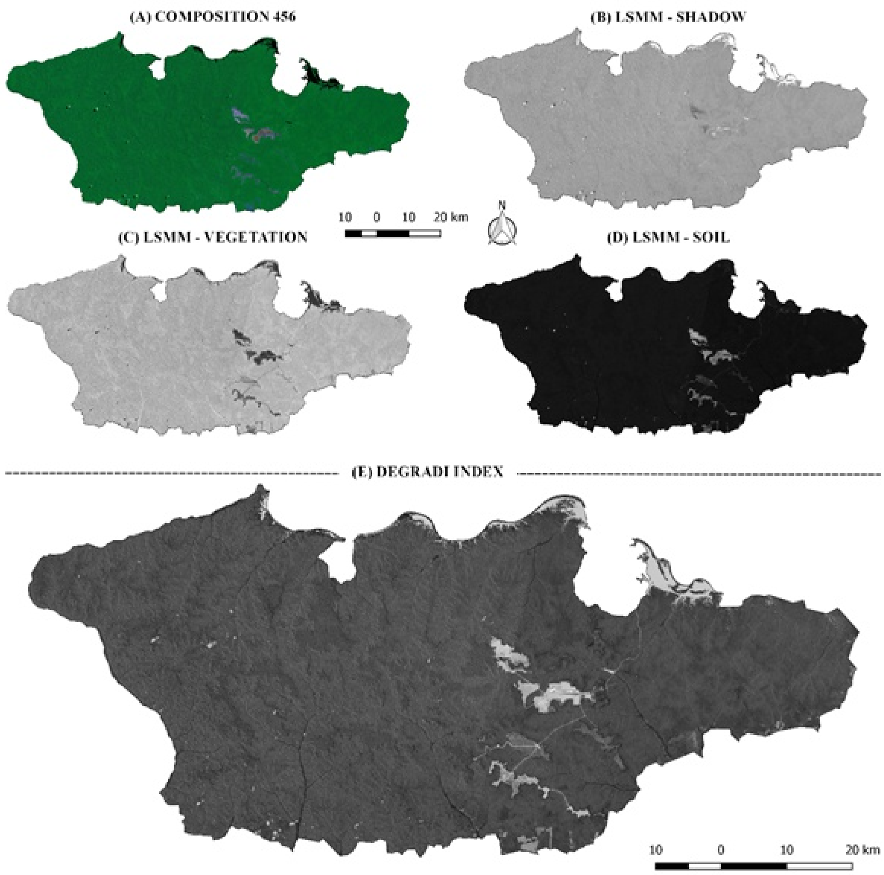

Figure 3. False color composition 456 (A), shadow/water fraction images (B), vegetation (C) and soil (D) and Spectral Index of Forest Degradation of the Saracá-Taquera National Forest in 2020.

Figura 3. Composição falsa-cor 456 (A), imagens-fração sombra/água (B), vegetação (C) e solo (D) e Índice Espectral de Degradação Florestal da Floresta Nacional de Saracá-Taquera no ano de 2020.

The results of the application of the linear spectral mixture model (LSMM) can be seen in figures 3B, 3C, and 3D, which represent the fraction-images: shadow/water, vegetation, and soil, respectively. According to Shimabukuro *et al.* (1998), the light areas in these images indicate the highest proportion of shadow/water, vegetation, or soil components in each pixel. From the observation of these images and comparing them with the composite image, it can be seen the highlight in the three analyzed components, which confirms the adequacy of the LSMM model for the identification of explored areas in FLONA-ST.

The analysis of the soil fraction (Figure 3D) allowed us to observe deforested areas in the central region and the upper and lower limits of FLONA-ST, mainly in the areas belonging to the municipalities of Oriximiná and Terra Santa. The deforested areas with polygonal features and regular shape in the central portion of the CU are characteristic of mining and tailings deposit areas, therefore, they are associated with mining activity. The presence of well-defined linear features, characteristics of roads that guarantee access to these areas, reinforce this statement, which was confirmed after consulting the FLONA-ST Management Plan (STCP, 2001).

According to the CU zoning, 142,095.47 ha (33.08% of the total area) are used in bauxite extraction, which has been carried out by the company Mineração Rio Norte (MRN) since 1967, and whose activity was authorized by Decree 98.704/ 1989 of creation of the CU. Despite being a licensed activity, it is worth remembering that mining is among the activities that most cause environmental degradation, with major losses in biodiversity, soil contamination, and problems for the health of the local community (Reis, 2006).

Mechi & Sanches (2010) report that in mining areas, environmental impacts associated with the suppression and/or impediment of vegetation regeneration, removal of surface soil, change in the quality of the river, reservoir, and underground water, air pollution by particulates suspended from mining activity, noise and ground vibrations associated with equipment operations and explosions. Furthermore, tailings, obtained from the treatment of raw ore, are one of the main forms of contamination of soil and water by heavy metals (Muniz *et al.*, 2006).

Regarding deforested areas north of FLONA-ST, there is a trend towards greater concentration in places close to watercourses such as rivers and lakes. According to the UC Management Plan, the area given for occupation and use by traditional populations living within the National Forest (Population Zone), with an extension of 10,690.75 ha (2.49% of the total area), is located, mainly, in the northern portion of the CU on the right bank of the Trombetas River. Thus, the identified features can be associated with areas of housing and agricultural activities performed by traditional riverside communities and remaining from quilombos that occupy the region and have their permanence legally guaranteed by Decree 98.704/89, provided that its activities are compatible with the planned management programs for FLONA-ST (STCP, 2001).

Other more or less regular polygonal features were identified in the south, southeast, east, and northeast regions of FLONA-ST. Corroborating these findings, the CU Management Plan reports the occupation and illegal use of land by non-traditional communities that settled in the CU after its creation, which are mainly found in marginal areas to the south, southeast, east, northeast, and north of FLONA-ST, on the banks of Lake Potata, streams and roads (STCP, 2001).

It could have been observed in consultation with the database of the Rural Environmental Registry of Pará (CAR), managed by the State Secretariat for the Environment and Sustainability (SEMAS), that most of the soil areas exposed to the south, are considered consolidated and are within the limits of rural properties registered in the Environmental Regularization Program. It should be observed that, according to § 1st of Article 17 of Law n. 9.985/00, "the FLONA's are in public possession and domain, and the private areas included in their boundaries must be expropriated". It was not the objective of this work to make a more in-depth analysis of the situation of rural properties entirely or partially located within the limits of the Saracá-Taquera forest. However, the evident overlapping of properties in the area of the CU suggests the need for a careful study to clarify the presence of properties registered in the Environmental Regularization Program, whose limits are included in FLONA-ST.

Although the soil fraction-image (Figure 3D) had already shown the deforested areas within the CU, it was observed that the application of the Forest Degradation Spectral Index (DEGRADI) highlighted the elements indicating forest exploitation, which enabled the detection of the typical selective cutting patterns of wood in the south-central, south and east portion of FLONA-ST (Figure 3E).

The signs of forest activity in the region are justified, mostly by the forest concession granted by the Brazilian Institute for the Environment (IBAMA) to three companies (Ebata Produtos Florestais Ltda.; Samise Indústria Comercio e Exportação Ltda.; Golf Indústria e Comércio de Madeiras Ltda.) for the exploitation of timber and non-timber forest resources in the FLONA. This is because Decree No. 98,704 authorizes IBAMA to enter into agreements with private companies aiming at the sustainable exploration of resources in the Conservation Unit (CU).

According to data available from the Brazilian Forest System, these companies operate on a total area of 135.100 hectares. The company Ebata Produtos Florestais has a forest concession to operate in two Forest Management Units (FMU) in the forest, one with 26.898 ha (FMU Ia) and the other with 30.000 ha (FMU II). The company Samise Indústria Comercio e Exportação was given a forest concession to explore 59.408,34 ha (FMU Ib); and the Company Golf Indústria e Comércio de Madeiras is authorized to explore 18.794 ha (FMU III). Figure 4 shows the location of these units.

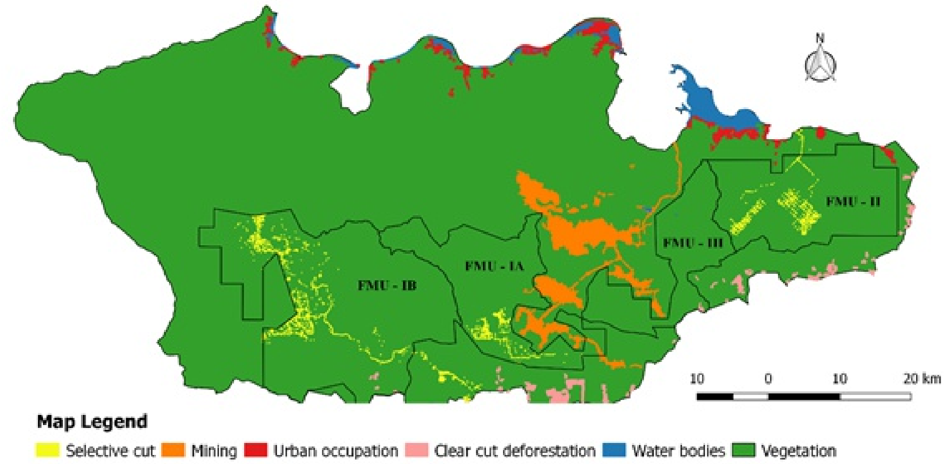

Figure 4. Result of the slicing of levels, vectorization and visual interpretation of the image generated from the DEGRADI index in image registered in Florestal in the Saracá-Taquera National Forest in the year 2020.

Figura 4. Resultado do fatiamento de níveis, vetorização e interpretação visual da imagem gerada a partir do Índice DEGRADI em imagem registrada na Florestal na Floresta Nacional de Saracá-Taquera no ano de 2020.

Figure 4 shows more clearly and with a greater sharpness the mining areas and also the urban occupation and deforestation areas as well as the signs of forest management caused by disorderly selective logging and or geometric (Souza *et al.*, 2019). Signs of disorderly selective logging were observed in FMU-IA and FMU-1B while signs of geometric logging were found in FMU-II.

Associated with selective logging patterns, the presence of skid trails, secondary roads, and storage yards was found, which confirm the practice of forest management in FLONA-ST. It is paramount to highlight that the Reduced Impact Exploration (RIR) is one of the principles of sustainable forest management from a scientific and legal point of view.

Signs of forest exploration were not identified in FMU-III. Such signs may be related to the low spatial resolution of the sensor used for the acquisition of the images (30 m) and the dimensions of the elements indicating forest degradation, particularly those associated with selective exploration. According to Capanema *et al.* (2016), signs of forest degradation in areas of low exploration intensity maybe easily identified in a field study but in orbital images with a 30-m spatial resolution such as the OLI sensor of LANSAT 8 satellite they may be mistaken with forest areas due to the dense forest canopy that covers most of FLONA-ST.

The hypothesis suggested in the previous paragraph explains why no clear signs of forest exploitation were found in the FMU III, although it is public knowledge the existence of forest management activity in the Unit. According to the technical execution summary of the FMU's concession provided by the Brazilian Forest Service associated with the Ministry of Agriculture and Supply, from 2012 to 2016, 71,174.58 m³ of logs have already been extracted in the FMU III, generating a collection of R$ 5,876,515.45. In relation to FMU II, 190,979.93 m³ of logs were removed from 2012 to 2020, with a collection of R$18,201,782.72. In the FMU Ia and Ib, 95,141.00 m³ and 196,100.13 m³ of logs were extracted from 2015 to 2020, respectively, which generated a collection of R$3,932,727.19 in the FMU Ia and R$14,618,620.06 in the FMU Ib. Considering the sum of these data in the four FMU's, 197,782.16 m³ of logs have already been extracted, which resulted in a collected amount of R$ 15,348,728.76.

Table 1 shows the absolute values and percentages of the areas identified in this study. Among the identified anthropic activities, mining was the one with the largest extension of area with 9183.91 ha, which is equivalent to 2.08% of the total area of FLONA-ST. Next is the urban occupation class with 2573.64 ha (0.58%). Clear-cut deforested areas totaled 2319.84 ha (0.53%), while selective logging areas (geometric and disordered) totaled 1657.08 ha (0.38%). Considering all these classes, it is observed that the percentage of altered area is approximately 3.57%, which suggests that 96.43% of the FLONA-ST surface is covered by vegetation (418001.48 ha - 94.72%) and water (7513.83 ha - 1.71%).

Table 1. Quantification of mining areas, urban occupation, clear cut deforestation, selective cut, water bodies e vegetation in Florestal in the Saracá-Taquera National Forest in the year 2020.

Tabela 1. Quantificação das áreas mineração, ocupação urbana, desmatamento com corte raso, corte seletivo, corpos d'água e vegetação na FLONA de Saraca-Taquera no ano de 2020.

Class	Area	
	ha	%
Mining	9183.91	2.08
Urban occupation	2573.64	0.58
Clear cut deforestation	2319.84	0.53
Selective cut	1657.08	0.38
Water bodies	7513.83	1.71
Vegetation	418001.50	94.72
Total	441282.63	100.00

In general, the Sacará-Taquera Conservation Unit has fulfilled its role in the conservation of the Brazilian Amazon biome as it has extensive vegetation cover. However, this CU is threatened by commercial interests, legalized or not, which could affect the availability of these natural resources in the future. This is because the removal of the vegetation cover identified in this study puts at risk the edaphic stabilization and quality of watercourses (LIMA *et al.*, 2016).

It is worth mentioning that, except for the selective logging areas, the minimum limit for image classification was 6.25 ha for images with a spatial resolution of 30 m, according to Souza *et al.* (2019). Thus, it is possible that if the study had been carried out using images with better spatial resolution, other areas of exposed soil could be highlighted, thus increasing the precision of the study. Despite this, it is understood that the images in this study expose a current and unique knowledge to assist in public actions aimed at the protection, conservation, and inspection of natural resources (timber or not) in the FLONA of Saracá-Taquera, being, therefore, an important tool for monitoring exploration and occupation areas within the Conservation Unit.

4 Conclusion

The use of the spectral mixture linear model and the Forest Degradation Spectral Index were adequate to identify the deforested areas in the Saracá-Taquera Forest.

In general, the Sacará-Taquera National Forest predominated in areas covered with dense and heterogeneous vegetation. However, deforested areas were observed in the central, north, northeast, southeast, and south portions, whether destined for mining, agricultural activities, housing, or for the exploitation of forest resources.

The indications of forest exploitation in the National Forest were mostly observed within the Forest Management Units, where exploration by disordered and geometric selective logging was observed.

Acknowledgements: To the United States Geological Service (USGS) for providing the orbital images used in this research. To the Federal Institute of Education, Science and Technology of Pará (IFPA) and the Federal Rural University of Amazonia (UFRA) for their institutional support. To the IFPA GESMABA and NUPECSA research groups for their operational support.

Contribution of the authors: Michel Keisuke Sato: Conceptualization, Data Curatorship, Formal Analysis, Research, Methodology, Project Management, Software, Visualization, Writing – First Writing; João Almiro Corrêa Soares: Conceptualization, Data Curatorship, Formal Analysis, Methodology, Project Management, Software, Supervision, Validation, Writing – Review and Editing; Bruna Naiara Rocha: Conceptualization, Formal Analysis, Research, Methodology, Visualization, Writing – Review and Editing; Cássio Furtado Lima: Conceptualization, Formal Analysis, Research, Methodology, Visualization, Writing – Revision and Editing.

Sources of funding: There was no source of funding.

Conflict of interest: The authors declare no conflicts of interest.

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