SPECTRAL DIVERSITY AS A REMOTE SENSING TOOL FOR MONITORING ENVIRONMENTAL QUALITY IN REHABILITATED ECOSYSTEMS

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RESUMO

A recuperação de áreas degradadas por atividades de mineração é crucial para mitigar impactos ambientais. Este estudo teve como objetivo avaliar a qualidade ambiental de áreas mineradas na Amazônia Oriental, utilizando a diversidade espectral de imagens de satélite. Foram analisadas quatro áreas de restauração florestal para compensação e três áreas mineradas em recuperação nos municípios de Parauapebas, Canaã dos Carajás e Ourilândia do Norte, no Pará. O índice de Shannon , variou de 0 a 3,03 para a diversidade espectral, enquanto o status ambiental variou de 0 a 100. Encontramos uma correlação positiva entre diversidade espectral e qualidade ambiental medida em campo, indicando que a diversidade espectral é um bom indicador de recuperação. No entanto, em áreas com status e diversidade espectral altos, a correlação foi mais fraca. Esses resultados sugerem que a diversidade espectral é útil para monitorar a recuperação, mas a inclusão de variáveis adicionais pode aprimorar a análise.

Palavras-chave **—** Impactos ecológicos, monitoramento remoto, restauração florestal, biodiversidade.

ABSTRACT

The recovery of areas degraded by mining activities is crucial for mitigating environmental impacts. This study aimed to assess the environmental quality of mined areas in Eastern Amazon using spectral diversity from satellite images. Four compensation areas and three recovery areas were analyzed in the municipalities of Parauapebas, Canaã dos Carajás, and Ourilândia do Norte, in Pará. The Shannon index, calculated using the BiodivMapR package, ranged from 0 to 3.03 for spectral diversity, while the environmental status varied from 0 to 100. We found a positive correlation between spectral diversity and field-measured environmental quality, indicating that spectral diversity is a good indicator of recovery. However, in areas with high status and spectral diversity, the correlation was weaker. These results suggest that spectral diversity is useful for monitoring recovery, but the inclusion of additional variables could enhance the analysis.

Key words **—** *Ecological impacts, remote monitoring, forest restoration, biodiversity.*

1. INTRODUÇÃO

To mitigate the environmental impacts of mining, rehabilitation and restoration are implemented as distinct approaches. Rehabilitation aims to restitute ecosystem functions, while restoration seeks to fully reinstate ecosystem services to pre-disturbance conditions [1]. Effective ecological monitoring is essential to assess ecosystem resilience, track biodiversity recovery, and ensure progress toward ecological benchmarks. Traditional monitoring methods, while reliable, face limitations in spatial and temporal scales and are often costly [2]. In contrast, remote sensing offers a cost-effective way to evaluate large areas with high temporal frequency, making it crucial for monitoring recovery in mined areas [3].

Numerous studies have utilized remote sensing to characterize environmental features, monitor land cover changes, and track revegetation projects [4]. Advanced techniques such as LiDAR and multispectral sensors provide valuable insights, yet they often fail to capture the full complexity of ecological functions necessary for assessing environmental quality [2]. The heterogeneous nature of rehabilitated landscapes further complicates remote monitoring, requiring higher-resolution data to accurately assess recovery stages [2].

Tree diversity is recognized as a strong indicator of environmental quality in rehabilitated areas [5] and can be detected through high-resolution satellite data [6]. In addition, the spectral diversity hypothesis postulates that spectral variation reflects the functional characteristics of plant communities [7]. This study aims to explore spectral diversity as a tool for remotely assessing environmental quality in mined areas undergoing rehabilitation and restoration in Eastern Amazon. Utilizing freely available Sentinel-2 satellite imagery, we calculated spectral diversity as the Shannon index and correlated it with field-collected environmental quality data, enhancing our understanding of the relationship between spectral diversity and ecological health.

2. MATERIAL E METHODS

This study was conducted in the municipalities of Ourilândia do Norte, Canaã dos Carajás, and Parauapebas in the state of Pará, Brazil (Figure 1).

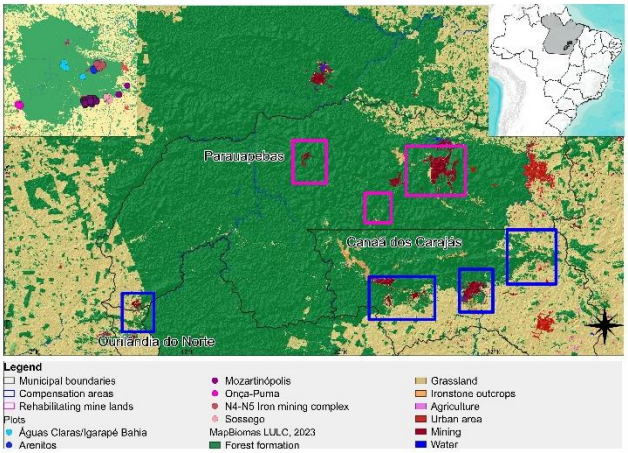

Figure 1. Location of the study on compensation/restoration areas.

Areas	Measurement	Remeasurement	State	Sentinel images
N4-N5	2017	2019	Rehabilitation	Sentinel-2 image from 2017-06-10 Sentinel-2 image from 2019-06-30
Águas Claras/ Igarapé Bahia	2021	-	Rehabilitation	Sentinel-2 image from 2021-05-30
Arenitos	2017	-	Rehabilitation	Sentinel-2 image from 2017-06-30
Mozartinópolis	2019	2021	Compensation	Sentinel-2 image from 2019-05-06 Sentinel-2 image from 2021-06-29
Mozartinópolis	2023	-	Compensation	Sentinel-2 image from 2023-06-29
Onça-Puma	2022	-	Compensation	Sentinel-2 image from 2022-05-28
Sossego	2022	-	Compensation	Sentinel-2 image from 2022-06-24

Table 1. Areas studied and the respective years of measurement, including re-evaluations and the Sentinel images used.

The environmental quality of rehabilitated and restored areas was assessed using nine key indicators covering community diversity, vegetation structure, and ecological processes, based on established monitoring criteria. In 10 x 20 m forest inventory plots, all trees with a DBH (diameter at breast height) ≥ 3 cm were identified to determine tree species richness, Shannon diversity, above-ground biomass, and functional and phylogenetic diversity. Soil organic matter was measured from composite samples (0-10 cm depth), and the leaf area index was also recorded. The Bray-Curtis index assessed similarity between recovery areas and native forests. A Restoration Index was derived from principal coordinate analysis (PCoA), integrating these indicators to gauge restoration progress [8, 9].

Sentinel-2 satellite images from the beginning of the dry period (May–June) were obtained from the Copernicus Hub with a 20% cloud cover limit to ensure clear views of each area. Spectral data was used to assess spectral diversity alongside environmental quality data from permanent georeferenced plots. Using the biodivMapR package in RStudio [6], non-vegetated and cloud-covered pixels were filtered out using a NDVI threshold of 0.3. A Blue threshold of Principal Component Analysis (PCA) reduced spectral data dimensionality, clustering pixels into 100 spectral species groups. Spectral diversity was then calculated in 50 x 50 m windows using the Shannon index, and values were correlated with field-based environmental quality data. Linear models, Pearson's correlation, and RMSE assessed the relationship between spectral diversity and environmental quality.

An additional variable, shade, was introduced as a vegetation cover index (ranging from 0 to 100) to assess its effect on spectral diversity and its correlations with environmental quality, as presented in Table 2. To investigate remeasurement effects, a comparative analysis was conducted between the N4-N5 areas (years 2017 and 2019) and Mozartinópolis (years 2019 and 2021). Finally, spectral data from 2023 in Mozartinópolis were used to examine changes in spectral diversity across monitoring points from 2019 to 2021, seeking evidence of successional advance.

3. RESULTS

3.1 Spectral diversity

The studied areas show variations in status and spectral diversity, reflecting distinct environmental dynamics and different phases of ecological succession. Spectral diversity ranged from 0 to 3.03, while environmental status values ranged from 0 to 100, depending on the successional stage and environmental condition of the sampling points. Temporal comparisons reveal an increase in spectral diversity in both Mozartinópolis and the N4-N5 mining complex, with Mozartinópolis increasing from 1.78 in 2018 to 2.60 in 2023, and N4-N5 from 1.81 in 2017 to 2.09 in 2019, both accompanied by slight improvements in environmental quality (Table 2).

Area	Year	Status	Spectral diversity	Vegetation cover
Águas Claras/Igarapé Bahia	2021	46.55	1.92	86
Arenitos	2017	67.62	2.07	88
Mozartinópolis	2018	39.75	1.78	83
Mozartinópolis	2021	71.86	2.49	96
Mozartinópolis	2023	78.68	2.31	99
Onça-Puma	2022	27.95	1.35	98
N4-N5	2017	46.53	1.81	80
N4-N5	2019	47.66	2.09	81
Sossego	2022	74.74	2.53	100

Table 2. Average values of Status, spectral diversity and vegetation cover for each area.

A trend was observed where areas with higher environmental status values also exhibited greater spectral diversity, suggesting that ecosystem condition health influences spectral variability. However, the strongest correlations between status and spectral diversity were seen in areas with lower environmental quality and lower spectral diversity, while areas with high values for both indicators showed weaker correlations.

3.2 Correlation between spectral diversity and status

Among the studied areas, Onça-Puma exhibited the highest correlation, with low status (27.95) and a spectral diversity of 1.35. The coefficient of determination (R^2) was 0.74, indicating that 74% of the variation in environmental status is explained by variations in spectral diversity, with an RMSE

of 32.14, the lowest among the areas, suggesting a good model fit to local conditions (Figure 2).

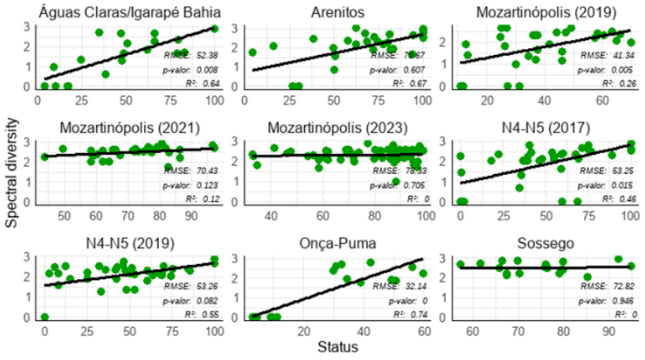

Figure 2. Correlation between status and spectral diversity, showing RMSE values, p-values, and R^2 for each area.

In contrast, areas like Sossego and Mozartinópolis (2023) had high values for both status and spectral diversity but showed nearly no correlation between these variables (r^2 of 0.00), with high RMSE values (70-72). The high RMSE (70~72) in these areas reveals a considerable margin of error in the predictions, indicating that the model has more difficulties to capture the relationship between environmental status and spectral diversity in these contexts. Figure 3 illustrates the environmental status and spectral diversity values for one of the study areas, Sossego.

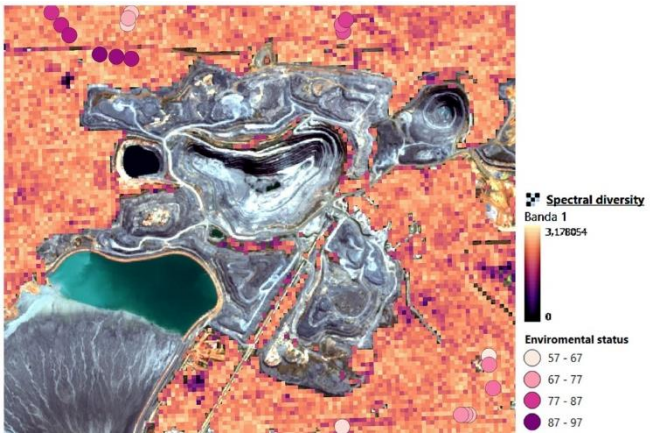

Figure 3. Environmental status and spectral diversity values for the Sossego area.

4. DISCUSSION

Spectral diversity from Sentinel-2 images showed a positive correlation with environmental quality in forest recovery areas near the Carajás National Forest [7]. However, as recovery progresses, factors like soil type and biomass influence spectral variability, weakening this correlation and indicating the need for their inclusion to enhance prediction accuracy.

Distinctly, Mozartinópolis serves as a forest compensation area, while N4-N5 is a degraded mining site, resulting in slower recovery in the latter. Preliminary analyses revealed lower root mean square error (RMSE) in rehabilitated mining areas compared to forest compensation sites, suggesting better model performance in capturing recovery dynamics.

The relationship between spectral diversity and environmental status varies, with higher vegetation cover (e.g., Onça-Puma) showing stronger correlations. Conversely, areas with lower cover (e.g., N4-N5) display moderate correlations, while Mozartinópolis (2023) exhibited high shade cover but no significant correlation, highlighting the importance of land management.

In Onça-Puma, pasture areas contribute to lower status values despite good cover, as high biomass density can enhance spectral diversity correlations, but pasture uniformity can reduce overall diversity.

These findings indicate that while spectral diversity can serve as a robust indicator of environmental quality in certain areas, in others, additional environmental variables or more complex modeling approaches may be needed to better capture this relationship.

Overall, higher environmental quality typically correlates with increased spectral diversity, particularly in older rehabilitated stands, while lower values are linked to non-revegetated areas like tailings basins. Well-preserved areas often show weaker correlations due to ecological variability and indicator saturation.

5. CONCLUSION

This research highlights the effectiveness of remote sensing, particularly spectral diversity analysis, in monitoring forest restoration and mineland rehabilitation across different projects. However, its effectiveness decreases in advanced recovery stages and compensation areas, where vegetation can become homogeneous, limiting spectral variation and ecological assessment accuracy.

While the correlations between status and spectral diversity confirm the methodology's effectiveness in lower-quality environments, future studies should include additional environmental variables—such as land cover, species composition, biodiversity indices, and climatic factors—to capture the complexities of environmental disturbances and their local and regional influences. This integration would enhance the understanding of the dynamics affecting spectral diversity and improve assessments of environmental quality in rehabilitating and restoring ecosystems.

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