An Acad Bras Cienc (2024) 96(3): e20230236 DOI 10.1590/0001-3765202420230236
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

ECOSYSTEMS

Indicators to quantify biodiversity gains for compensation and mineland rehabilitation in the Eastern Amazon

PRISCILA S. DE MEDEIROS-SARMENTO, ARIANNE F. DE CASTRO, FERNANDA V. PENNER & MARKUS GASTAUER

Abstract: To connect the protection of natural resources to economic development, environmental rehabilitation is a promising way to repair and compensate for impacts on biodiversity and ecosystem services. Here, we aimed to compare and select potential indicators for the success of different rehabilitating ecosystems to quantify gains in biodiversity and ecosystem services within the Impact Mitigation Hierarchy. We sampled nine environmental variables along rehabilitation chronosequences from rehabilitating (i) iron mining waste piles, (ii) sand quarries, and (iii) compensation areas in the Carajás National Forest. From that, we computed the rehabilitation status, i.e., the proportion of environmental enhancements compared to the overall rehabilitation trajectory, and statistically validated the indicators that best described the status. With a mean rehabilitation status for the oldest rehabilitation stages from waste piles, sand quarries, and compensation areas of 52, 71, and 74%, respectively, we confirmed that rehabilitation activities were able to generate considerable gains in biodiversity. In all the cases, the Shannon diversity, phylogenetic diversity and Leaf Area Index performed better than did the other indices, encouraging the increased use of these indices for upscale monitoring activities. Consistent indicators across distinct projects highlight the importance of maximizing tree diversity and canopy closure in rehabilitation projects to increase biodiversity gains within Impact Mitigation Hierarchy.

Key words: Biodiversity, Carajás National Forest, corporate traceability, Impact Mitigation Hierarchy, environmental monitoring, rehabilitation status.

INTRODUCTION

Economic activities such as mining exert significant pressure on natural ecosystems, impacting biodiversity and ecosystem services (e.g., Biney et al. (2022)). The Impact Mitigation Hierarchy connects the protection of natural resources to economic development through the avoidance, minimization, reparation and compensation of environmental degradation (Maron et al. 2018, Gelot & Bigard 2021). Its implementation is expected to result in zero net impact (No Net Loss) and may even promote positive impacts (Net Gain, (Rainey et al. 2015)). Therefore, environmental rehabilitation, i.e., the restitution of biodiversity and ecosystem services as close as possible to predisturbance levels (Gastauer et al. 2018), aims to repair degraded ecosystems or compensate for residual degradation by human activities (Ahmad et al. 2022, Gann et al. 2019, Guerra et al. 2020). The project-specific success of rehabilitation activities depends on the type and degree of disturbance, rehabilitation strategy and time and environmental conditions, which may differ temporarily or permanently from those of mature, old-growth ecosystems (Crouzeilles et al. 2016). Thus, the monitoring and evaluation of biodiversity gains are necessary to quantify the resulting biodiversity gains within the Impact Mitigation Hierarchy (Lamb et al. 2015, Lechner et al. 2018, Mazón et al. 2019).

Good environmental monitoring practices compare environmental conditions with desired rehabilitation outcomes, and additional comparisons with degraded areas are necessary to quantify the current performance of rehabilitating areas and the way ahead (Gastauer et al. 2018). To understand the full complexity of rehabilitating ecosystems, multidisciplinary and multivariate approaches have been proposed (Mukhopadhyay et al. 2014, Kollmann et al. 2016, Gastauer et al. 2019a, Bandyopadhyay et al. 2020). This approach increases the number of variables that may be evaluated for such assessments (Prach et al. 2019), although the identification and validation of easily measurable, effective indicators may reduce the costs and labor costs of environmental monitoring programs in practice (Gastauer et al. 2020, 2021).

Derived from primers for ecological restoration (SER 2004), indicators of the key ecological attributes of vegetation structure, community composition, and ecological processes are considered mandatory (Wortley et al. 2013, Gann et al. 2019). From such field-surveyed indicators, the definition of biodiversity values of rehabilitating sites, e.g., the proportion of achieved environmental enhancements compared to the overall trajectory from nonrehabilitated to reference sites, is possible using statistically sound and unbiased multivariate methods (Gastauer et al. 2020) and allows the quantification of biodiversity gains within the mitigation hierarchy (Oliver et al. 2021). Furthermore, the unambiguous definition of the rehabilitation status permits the validation of potential environmental indicators to simplify monitoring procedures (Gastauer et al. 2020). From a set of 27 environmental variables, the Shannon index of tree diversity was identified as the most promising indicator for upscaling mineland monitoring activities (Gastauer et al. 2021), but the generality of such validated indicators across projects remains a vital gap in our understanding of the rehabilitation process.

The objective of this study was to compare and select potential indicators for the success of different rehabilitating ecosystems in the eastern Amazon to quantify gains in biodiversity and ecosystem services within the mitigation hierarchy. Therefore, we integrated nine environmental variables collected across different rehabilitation chronosequences into a single estimation of rehabilitation status using a multivariate approach. The analyzed chronosequences cover rehabilitating iron mining waste piles, sand quarries and compensation areas from the Carajás National Forest and its adjacent areas and include nonrevegetated, degraded minelands and farmlands; different rehabilitation stages; and undisturbed evergreen Amazonian forest as the target ecosystem in all three cases. We derived the indicators that best described the overall rehabilitation status among all the field-surveyed environmental variables via statistical modeling.

MATERIALS AND METHODS

Study sites

This study was carried out in the Carajás National Forest, eastern Amazon, Brazil (Figure 1). The region is characterized by a tropical seasonal climate, Aw in the Koeppen classification, with a total precipitation of approximately 2,000 mm and daily mean temperatures above 24°C throughout the year (Alvares et al. 2013). Precipitation is concentrated between October and April, and monthly rain does not surpass 60

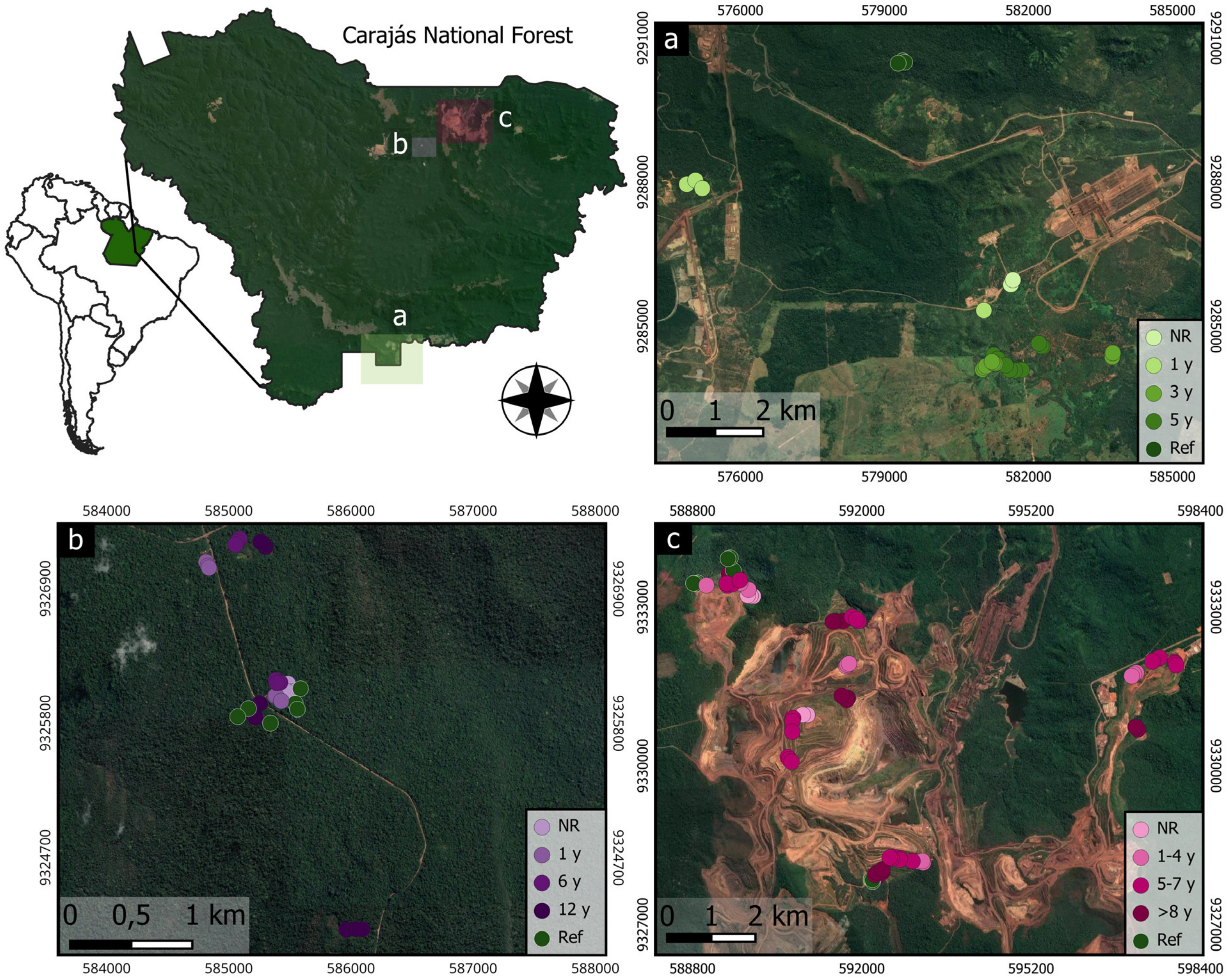

Figure 1. Location of the Carajás National Forest and permanent plots from compensation areas in the neighborhood of the protected area (a), waste piles within the N4-N5 iron mining complex (b), and sand quarries (c). Plots are grouped within age classes. NRs are nonrehabilitated areas, and Refs are reference sites covered by undisturbed evergreen dense forests.

mm in the dry season from May to September. Semidecidual, evergreen dense or open submontane forests dominate the vegetation of the conservation unit, but patches of canga vegetation, i.e., ferruginous savanna formations characterized by rare and endangered diversity (Giulietti et al. 2019), can be found above ironstone outcrops on mountaintops (Viana et al. 2016).

The region harbors important mineral reserves, including gold, manganese, nickel, copper, and iron (Rosière & Chemale 2000). Ores are extracted by open-cast mining; for that purpose, the original vegetation cover and eventual overburden are removed. The overburden is deposited next to the mining pits, forming large waste piles (Gastauer et al. 2022). The extraction of some minerals, such as gold, manganese or copper, results in the production of large amounts of tailings, which are generally deposited in tailing ponds (Gastauer et al. 2022).

Rehabilitation activities in the Carajás National Forest aim to restitute biodiversity and ecosystem services as close as possible to the natural reference values and are carried out to repair and/or compensate for the impacts of mining on ecosystems. Adopted rehabilitation strategies are context specific and include topsoil application, seedling planting, and hydroseeding (Ribeiro et al. 2018, Guedes et al. 2021). Here, we compile data from three different cases, (i) iron mining waste piles (Gastauer et al. 2021), (ii) sand quarries filled with mining waste and topsoil (Gastauer et al. 2019b), and (iii) seedling plantations in abandoned pastures, to offset mining impacts and increase forest cover and connectivity in adjacent conservation units (Gastauer et al. 2024). The declared rehabilitation targets in all cases were evergreen dense rainforests.

Due to the division of steep benches (up to 30°), waste piles from the N4-N5 mining complex are generally hydroseeded using a standardized mixture of fertilizers, organic compost and seeds of mainly nonnative, noninvasive, fast-growing grasses (e.g., *Avena strigosa* Schreb., *Pennisetum glaucum* (L.) R. Br., both Poaceae), sunflower (*Helianthus annuus* L., Asteraceae), and nitrogen-fixing legumes (*Crotalaria spectabilis* Roth., *Stylosanthes macrocephala* M.B. Ferreira & S. Costa, *Canavalia ensiformis* (L.) DC. and *Cajanus cajan* (L.) Huth., Fabaceae). To encourage the long-term self-sustainability of these areas, seeds from native species are added (approximately 15% of the overall seed mixture). Native seeds are collected from natural ecosystems in the region by a seed-collecting cooperative.

Prior to rehabilitation, the sand quarries were filled with mining waste from a nearby granite quarry, which was covered by a 30 cm topsoil layer originating from a logging area in a nearby manganese mine (for details, see Gastauer et al. 2019). After topsoil spread, native tree seedlings were planted at high densities. Seedlings are produced in local tree nurseries using native seeds from the region.

To offset mining impacts, the responsible mining company purchased cattle ranching farms in the neighborhood of the Carajás National Forest and launched forest restoration by seedling plantation. The planting density was 1,667 seedlings/ha. Until canopy closure two or three years after planting, invasive African grasses are removed manually. All the seedlings were produced in local tree nurseries.

Sampling

In all three cases, we sampled vegetation and soils along rehabilitation chronosequences to measure the success of rehabilitation using nine environmental indicators. For that, we installed permanent plots of 10x20 m. The minimum distance among plots was 50 m. The waste pile spans five distinct waste piles, each harboring different rehabilitation stages ranging from nonrehabilitated areas to nine-year-old rehabilitation stages. With three plots per rehabilitation stage from each waste pile, we sampled a total of 54 rehabilitating and six nonrehabilitated plots. In the three Arenito sand quarries, 21 rehabilitation and three nonrehabilitating plots (again, three per stage from each quarry) were installed in stages of zero to twelve years of age. For the compensation dataset, we sampled 36 plots distributed among three nonrehabilitated pastures, and each of the three areas rehabilitated in the rainy seasons of 2015/16, 2016/17, and 2017/18. As the rehabilitating plots in this study were sampled twice—in 2018 and 2021—surveys resulted in a chronosequence ranging from 0 to 6 years. Nine nonrehabilitated plots in this study were placed in neighboring pastures used for cattle ranching. To compare rehabilitating sites with rehabilitation targets, we installed 18 plots in undisturbed natural forests in the region (Figure 1).

Within plots, we tagged and identified all trees with diameters at breast height (dbh) greater than 3 cm until the species level. From this inventory, we derived the environmental indicators of tree density (number of trees), species richness and Shannon diversity for each plot. Given the difficulties in identifying small trees and treelets from vegetative stages, we used the number of trees with dbh between 3 and 5 cm as a surrogate for the number of recruits. We pruned the family phylogeny R20160415.new to all species found in this study (Gastauer & Meira-Neto 2017) and dated it using age estimates from Magallón et al. (2015) before we computed phylogenetic diversity using the picante package (Kembel et al. 2010) in the R environment (R Development Core Team 2020). For each species found in this survey, we gathered wood density (Chave et al. 2009), ecological strategy, and dispersal and pollination syndrome information from the literature and computed functional diversity using the FD package (Laliberté & Legendre 2010). Additionally, we measured tree height with a digital hypsometer and computed aboveground biomass from wood density, dbh and height (Chave et al. 2014).

In each plot, we measured the Leaf Area Index (LAI, i.e., the one-sided green leaf area per unit ground surface area) as a measure of canopy closure, primary productivity and evapotranspiration. Field measurements were carried out using LAI-2200C sensors (LI-COR Inc., Lincoln, NE, USA) following the manufacturer's instructions. For that, sky conditions were continuously monitored by a sensor at a site free of vegetation (above-canopy readings), and a second sensor was used to capture two below-canopy readings at each corner and at the center of each plot, totaling 10 below-canopy readings for each plot.

We collected a composite soil sample from each plot and determined the soil organic carbon content using the Walkley-Black method (Teixeira et al. 2017). Soil organic carbon exerts positive effects on soil physical and chemical properties and the soil's capacity to provide regulatory ecosystem services (Lal 2009). The nine indicators were grouped into key ecological attributes (i) vegetation structure (tree density, number of recruits, LAI), (ii) community diversity (Shannon diversity, similarity to reference sites, phylogenetic diversity), and (iii) ecological processes (functional diversity, AGB, soil organic carbon), as proposed by Wortley et al. (2013).

Data analysis

All analyses were carried out in the R environment. To compare species diversity among cases, we used the 'iNEXT' function from the homonymous package to rarefy and extrapolated the 95% confidence intervals of the species-sampling curves from the species abundance distribution (Hsieh et al. 2016). To check for differences in the performance of single environmental indicators between rehabilitation stages from distinct sites, we used one-way analysis of variance (ANOVA), assuming sample independence of our observations, and tested for homoscedasticity and a normal distribution of residuals in each group. To identify significance levels between stages and sites, we carried out post hoc Tukey tests.

To compute rehabilitation status, we integrated all nine environmental indicators using a multivariate approach (Gastauer et al. 2021). In brief, this method uses a principal coordinate analysis to ordinate plots based on the performance of environmental indicators in Euclidean space. The rehabilitation status then measures the degree to which the rehabilitating plots became closer to the reference sites, weighted by the overall rehabilitation trajectory, i.e., the distance from the degraded areas to the rehabilitation targets/reference ecosystems

(Figure 2). By definition, the rehabilitation status of degraded areas is 0, and the value is 1 for reference ecosystems. The status of rehabilitating areas is thus the proportion of environmental advances already achieved in relation to the overall trajectory.

To determine the best indicator for rehabilitation status, we modeled rehabilitation status as a function of all nine indicators using linear models. We ranked indicators based on the root mean square error (RMSE) and Akaike's information criterion (AIC). While the AIC, commonly used for model selection, validates which indicator explains the greatest amount of variance (Burnham & Anderson 2002), the RMSE returns the average distance between the observed and the predicted data values and is thus a measure for forecasting quality (Montgomery et al. 2021). In both cases, the lower the statistic is, the better the model.

The Chapman-Richards model (Zeide 1993) was used to extrapolate the development of rehabilitation status for a period of 50 years.

RESULTS

Species richness and sampling effort

Overall, we sampled a total of 3,452 trees belonging to 282 species from 168 genera and 49 families. A total of 156 species were inventoried in the reference sites, 75 in waste piles, 97 in sand quarries and 49 in compensation areas (Figure 3). Weighted by sampling effort, the highest species diversity was detected at the

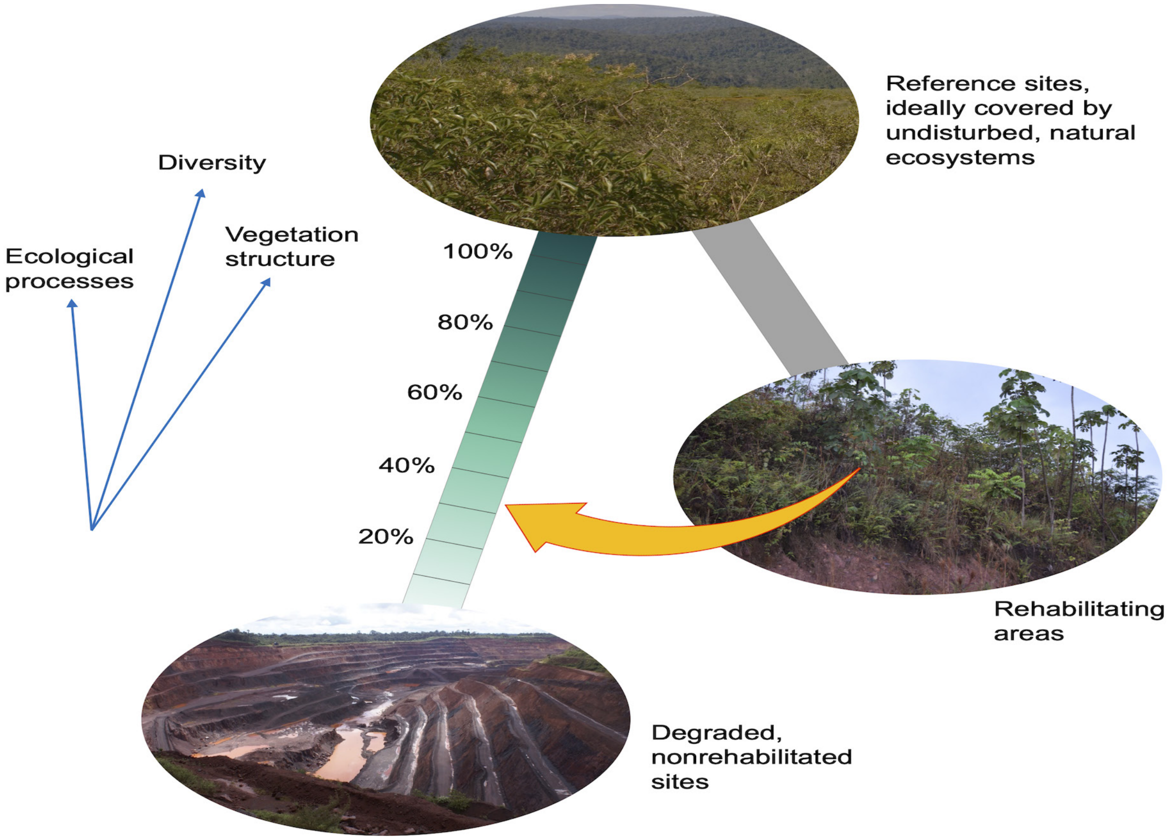

Figure 2. The principle of rehabilitation status. After ordinating degraded, nonrehabilitating, reference and rehabilitating sites in multivariate space using environmental variables (e.g., ecological processes, community diversity and ecological processes), the rehabilitation status describes the proportion of environmental enhancements compared to the overall trajectory from nonrehabilitated to reference sites (rehabilitation targets).

reference sites, while the sand quarries showed intermediate diversity. The lowest values, which did not differ significantly from each other, were found for compensation areas and waste piles.

Environmental indicators

The performance of most indicators in all three cases increased with rehabilitation time. Some of them, i.e., tree density, LAI (sand quarries only), tree recruitment (except compensation areas), soil organic matter and functional diversity, reach predisturbance levels in the oldest analyzed stages (Figure 4). Similarity to reference sites and above ground biomass show lowest performance when compared to reference surveys. Tree recruitment from compensation areas is highest in 3- to 4-year-old stands and tends to decline when rehabilitation advances. Soil organic matter showed no significant variation along the rehabilitation chronosequence in the compensation areas. Notably, the SOM contents in the sand quarries at the start of the rehabilitation chronosequence were similar to those in the waste piles and lower than those in the compensation areas, although these quarries received large amounts of topsoil.

Rehabilitation status and indicator selection

The computation of the rehabilitation status was straightforward, and the mean values for the oldest rehabilitation stages from waste piles, sand quarries, and compensation areas were 52, 71, and 74%, respectively (Figure 5). The maximum values reached 68% in 9-year-old waste piles, 81% in 12-year-old sand quarries

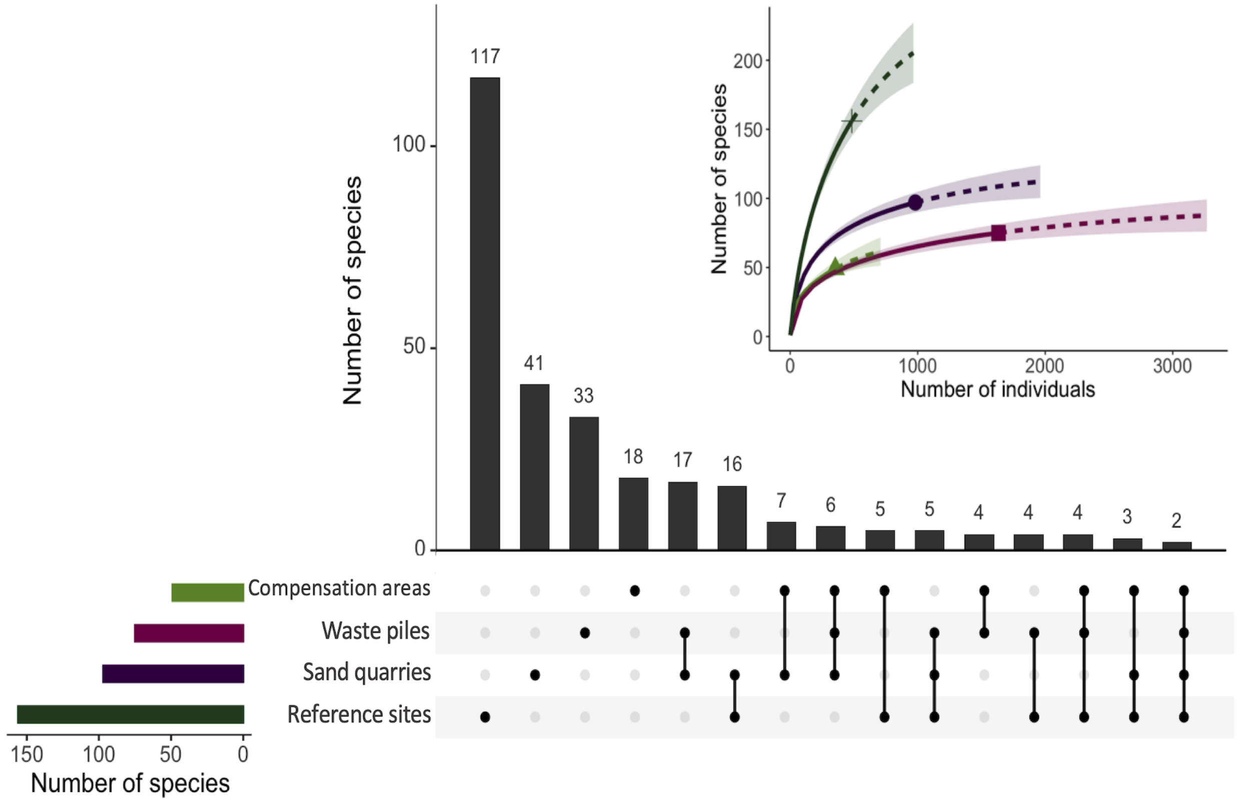

Figure 3. Number of exclusive and shared species of rehabilitating waste piles, sand queries and compensation areas as well as reference areas covered by natural forests free of disturbance from the Carajás National Forest, Pará, Brazil. Embedded figure: Interpolation (continuous lines) and extrapolation (dashed, shaded areas are 95% confidence intervals) for species diversity of the four habitats.

and 95% in 6-year-old compensation areas (data not shown). The indicator rank depends on the applied statistic and differs slightly among the analyzed cases, but in all cases, the indicators Shannon diversity, phylogenetic diversity and LAI performed better than did the others (Figure 6).

DISCUSSION

Here, we confirmed previous findings that rehabilitation activities were able to restitute high proportions of the original diversity, vegetation structure and ecological processes. Although chronosequences rather than true time series, i.e., space-for-time substitutions, were analyzed here, our data show that the performance of most environmental indicators increased with rehabilitation time in different rehabilitation projects. The differences in the individual performances of the indicators analyzed here make the development of integrated environmental monitoring fundamental for tracking impact mitigation contributions at the project level. Therefore, we used an unbiased, reliable multivariate approach (Gastauer et al. 2020, 2021) and estimated overall rehabilitation success from a set of variables following international recommendations regarding the evaluation of regrowing ecosystems (Gann et al. 2019). A rehabilitation status greater than 50% in all cases indicates that environmental rehabilitation of mine and farmland is an effective instrument for repairing and

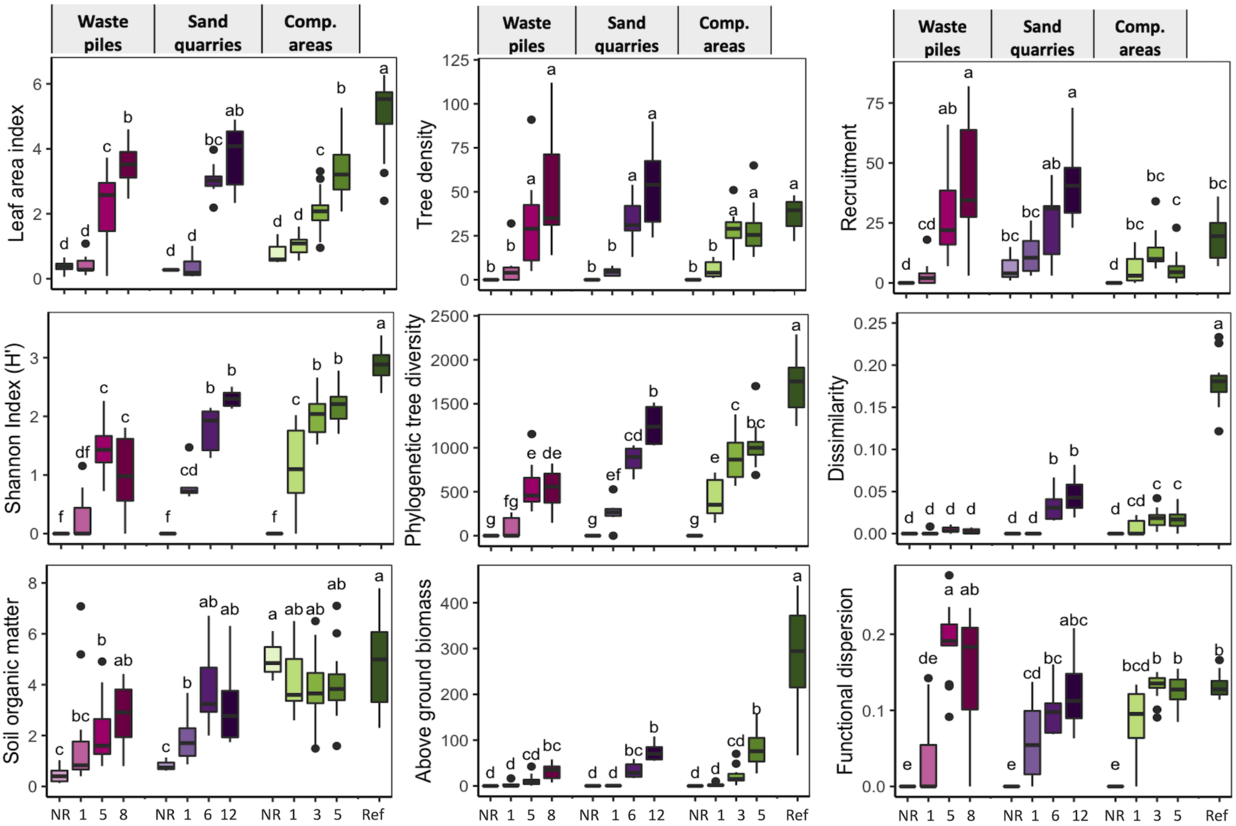

Figure 4. Nine environmental indicators were derived from vegetation and soils along chronosequences situated on iron mining waste piles, sand quarries and compensation areas in the Carajás National Forest and its neighborhood. Different letters indicate significant differences according to a post hoc Tukey test at $p < 0.05$.

compensating for environmental impacts such as those caused by mining within the principles of the mitigation hierarchy, especially when we assume that positive trends will continue in the future and that areas will continue to converge toward reference sites. For efficient future assessments, we propose a small set of environmental indicators that can be used to forecast rehabilitation quality across different projects.

The degree to which single field-surveyed environmental indicators recover varies among indicators and analyzed cases. First, low performance was detected for community composition (floristic similarity to reference sites) and aboveground biomass. This indicates the need to establish carbon-dominant secondary tree species to fully restitute predisturbance levels of biodiversity and ecosystem services. Second, functional diversity achieves (and exceeds) reference levels even in mid-aged rehabilitation stages according to the chronosequences analyzed here. This highlights the rapid establishment of principal plant functional types during rehabilitation, so increases in taxonomic and phylogenetic diversity with rehabilitation time contribute principally to functional redundancy and not the amplitude of ecological functions.

Finally, the high soil organic matter content along the entire rehabilitation chronosequence and the decline in recruitment rates after five years in rehabilitating compensation areas are noteworthy. High soil organic matter contents that did not differ from those at the reference sites demonstrated the maintenance

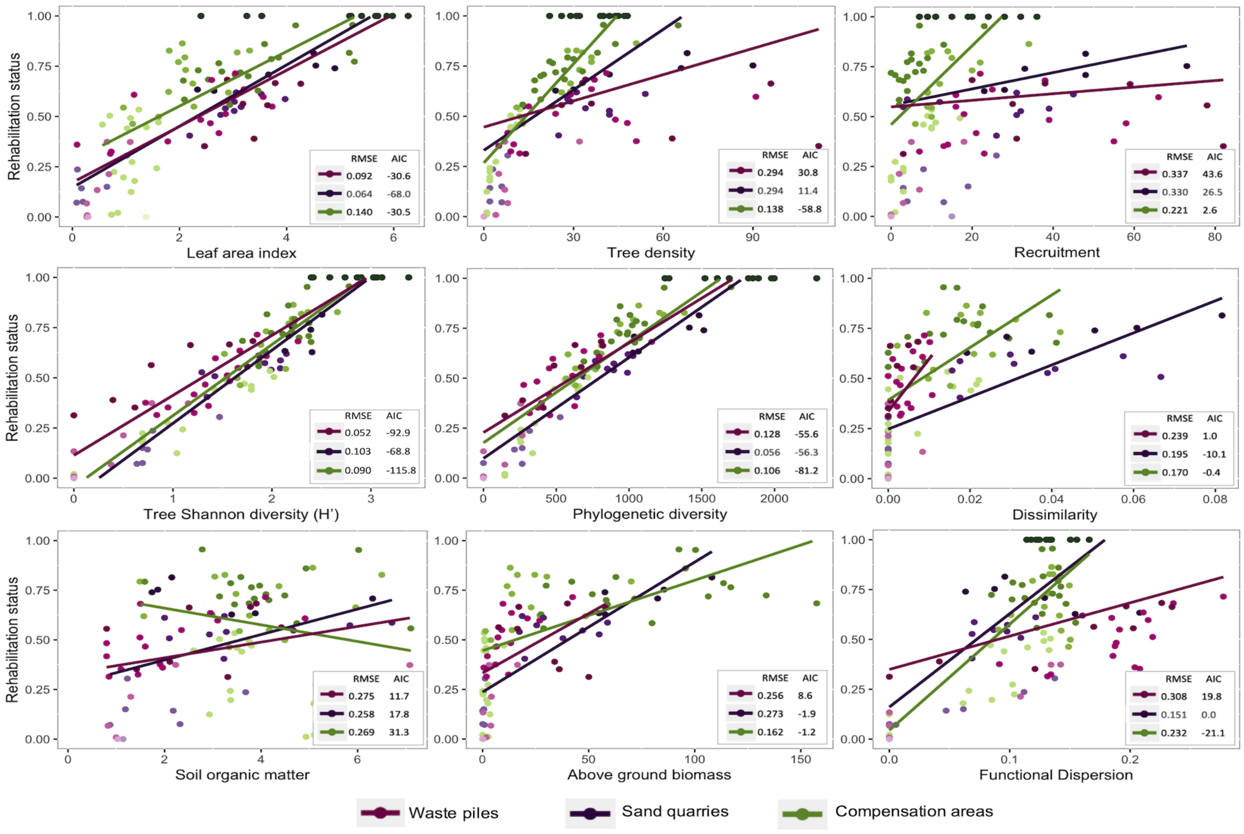

Figure 5. The observed and projected rehabilitation status as a function of rehabilitation time were derived from vegetation and soil indicators along chronosequences situated on iron mining waste piles, sand quarries and compensation areas in Carajás National Forest and its neighborhood.

of soil carbon stocks during logging and cattle ranching. In contrast, low soil organic matter contents at the beginning of mineland chronosequences indicate a greater degree of degradation compared to farmlands and need to be rebuilt, a process that took up to six years in the analyzed cases even when topsoil was applied, as in the sand quarries. Decreases in tree recruitment can result from a lack of connectivity between rehabilitated sites and native forest areas (Cerqueira et al. 2021) and delays in the maturity and seed production of planted trees, leading to pauperization of the soil seed bank and tree regrowth. To overcome such declines, enrichment planting or seeding of carbon-dominant, secondary forest species may be indicated.

Differences in the performance of single field-surveyed environmental indicators make indicator integration necessary to quantify biodiversity gains across projects, and the chosen multivariate method was straightforward for this purpose. The mean environmental status after 12 or fewer years of rehabilitation varied between 50% and 75%, demonstrating that rehabilitation activities set the trajectories of all areas on a desired course (Ahirwal & Maiti 2021). Although full ecosystem rehabilitation requires longer periods than those actually observed and further interventions such as enrichment plantings may be necessary, these figures indicate that considerable gains in biodiversity can be achieved by environmental rehabilitation within a mitigation hierarchy.

Greater biodiversity gains at shorter time intervals were detected for rehabilitation activities on abandoned farmland than for similar activities on minelands. This finding may be related to the degree of degradation that areas experienced prior to rehabilitation (Crouzeilles et al. 2016, Atkinson et al. 2022). Open-pit mining causes profound alterations at the landscape level due to intense earth movement, which leads to the formation of mine pits and waste deposits. Once, this brings substrates with high bulk densities to the surface, while disaggregated substrates without distinct soil layers arise from the filling of mine pits or the deposition of mining wastes and require the consolidation of organic matter contents and soil fauna communities. In contrast, farmlands (and especially pastures, as analyzed here)

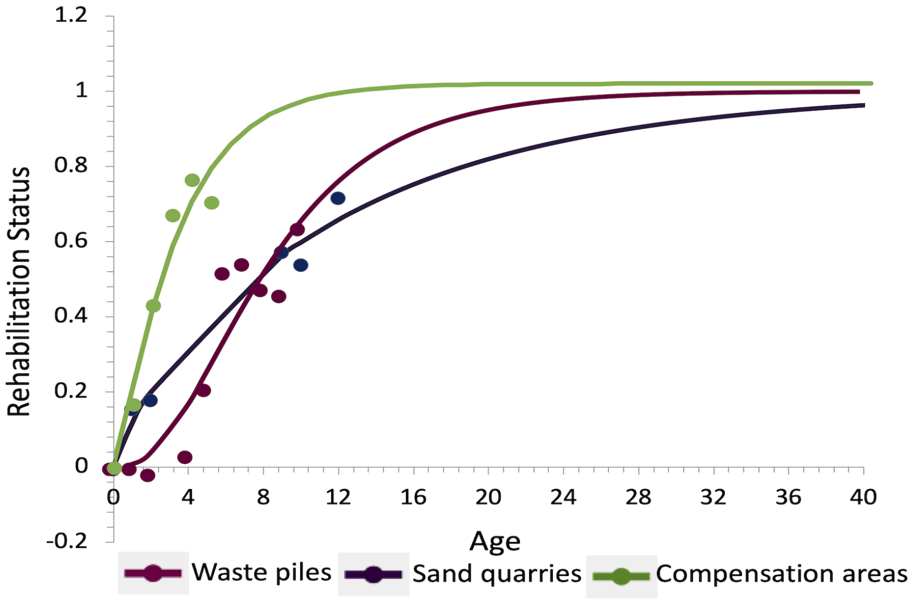

Figure 6. Relationships between environmental variables and rehabilitation status from chronosequences situated on iron mining waste piles, sand quarries and compensation areas in the Carajás National Forest and its neighborhood. Lines represent significant correlations, given the root mean square errors (RMSEs) and the Akaike information criterion (AIC).

suffer less intense degradation, maintaining the sequence of soil horizons, soil carbon stocks, microorganism communities and parts of the original seed bank. Interestingly, topsoil application, although showing benefits for the return of soil quality (Trindade et al. 2021), shows no significant benefit for rehabilitation success compared to waste pile hydroseeding, although studies on this topic are not conclusive.

In the analyzed cases, taxonomic and phylogenetic diversity as well as the leaf area index were the best indicators of overall rehabilitation status across all three cases analyzed here. They outperformed species richness and soil organic matter content, which were recommended as indicators for rehabilitation success in previous studies (Londe et al. 2017, Bandyopadhyay & Maiti 2019). The suitability of the Shannon index of tree diversity confirms previous findings from a smaller and shorter waste pile rehabilitation chronosequence (Gastauer et al. 2021), where its greater potential to forecast rehabilitation success was attributed to its lower sensitivity toward rare species populations. Phylogenetic diversity, a measure of feature diversity (Forest et al. 2007) with conservation value (Faith 2016), links an organism's taxonomic identity with ecosystem functionality, which highlights its importance as an indicator of rehabilitation success (Castro et al. 2022). Finally, the importance of canopy closure, e.g., measured as the leaf area index, for rehabilitation success and, although not analyzed here, the return of the fauna has been previously highlighted (Domínguez-Haydar et al. 2019, Serra et al. 2021). Differences in rehabilitation strategies, degree of degradation and environmental success among the cases did not affect indicator validation across different rehabilitation projects. This encourages the increased use of the three indicators leaf area index and taxonomic (Shannon) or phylogenetic diversity to quantify biodiversity gains across rehabilitation sites to simplify and reduce the costs of such environmental assessments.

On average, we detected the restitution of more than 50% of the original biodiversity in different mine and farmland rehabilitation projects from the Eastern Amazon a decade after implementation, which should be accounted for within the company's No Net Loss strategies. As no barriers for further convergence of the analyzed ecosystems toward reference forests were detected in this study, one might expect further biodiversity gains and increases in the environmental quality of these areas in the future. Specifically, our results highlight the importance of the taxonomic and phylogenetic diversity of the tree layer and canopy closure for rehabilitation success. This is because more diverse tree communities and denser canopies are associated with better environmental quality and better performance of ecological processes and structural parameters. Thus, maximizing tree diversity and canopy closure should increase biodiversity gains within rehabilitation projects. Canopy closure requires the planting of fast-growing species, and diversity may benefit from enrichment plantings, e.g., with carbon-dominant, secondary species.

CONCLUSIONS

Here, we test a framework to quantify the case-specific contribution of rehabilitation projects to the Impact Mitigation Hierarchy. The monitoring of nine environmental indicators along three rehabilitating chronosequences from the eastern Amazon reveals the changes in community diversity, vegetation structure, and ecological processes during the reparation and offset strategies of the mining industry. In all cases, considerable gains (> 50% in 12 or fewer years) in biodiversity within the Impact Mitigation Hierarchy were achieved, although the magnitude of the generated benefits differed among projects and depended on the degree of degradation, making project-level assessments necessary.

In three independent cases, the taxonomic and phylogenetic diversity and leaf area index were the best indicators for predicting the rehabilitation status, suggesting that these indices could be used to simplify future monitoring protocols. Their independent ability to upscale environmental monitoring across projects highlights the importance of maximizing tree diversity and canopy closure to increase and optimize biodiversity gains.

Acknowledgments

The authors are grateful for the financial support from Instituto Tecnológico Vale to carry out this study. Dr. Cecílio Frois Caldeira and Dr. Silvio Junio Ramos contributed to the survey design and data collection in the three case studies.

REFERENCES

AHIRWAL J & MAITI SK. 2021. Ecological restoration of abandoned mine land. Handbook of Ecological and Ecosystem Engineering 231-246.

AHMAD F, SAEED Q, SHAH SMU, GONDAL MA & MUMTAZ S. 2022. Chapter 11 - Environmental sustainability: Challenges and approaches. In: JHARIYA MK et al. (Eds), Natural Resources Conservation and Advances for Sustainability, Elsevier, p. 243-270.

ALVARES CA, STAPE JL, SENTELHAS PC, DE MORAES GONÇALVES JL & SPAROVEK G. 2013. Köppen's climate classification map for Brazil. Meteorol Z 22: 711-728.

ATKINSON J, BRUDVIG LA, MALLEN-COOPER M, NAKAGAWA S, MOLES AT & BONSER SP. 2022. Terrestrial ecosystem restoration increases biodiversity and reduces its variability, but not to reference levels: A global meta-analysis. Ecol Lett 25: 1725-1737.

BANDYOPADHYAY S & MAITI SK. 2019. Evaluation of ecological restoration success in mining- degraded lands. Environ Qual Manage 29: 89-100.

BANDYOPADHYAY S, NOVO LAB, PIETRZYKOWSKI M & MAITI SK. 2020. Assessment of Forest Ecosystem Development in Coal Mine Degraded Land by Using Integrated Mine Soil Quality Index (IMSQI): The Evidence from India. For Trees Livelihoods 11: 1310.

BINEY E, BINEY N, DADZIE I, HARRIS E, QUARTEY GA, ASARE YM, BESSAH E & FORKUO EK. 2022. Impact of mining on vegetation cover: A case study of Prestea Huni-Valley municipality. Scientific African, e01387.

BURNHAM KP & ANDERSON DR. 2002. Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach (2nd ed).

CASTRO AF DE, MEDEIROS-SARMENTO PS DE, CALDEIRA CF, RAMOS SJ & GASTAUER M. 2022. Phylogenetic clustering of tree communities decreases with stand age and environmental quality along a mineland rehabilitation chronosequence. Perspectives Ecol Conser 20: 279-285.

CERQUEIRA RM, JARDIM MA, JÚNIOR LL, PAIXÃO LP & MARTINS MB. 2021. Fitossociologia do estrato arbóreo em floresta nativa e em áreas do programa de recuperação de áreas degradadas sob influência da mineração, Paragominas, Pará, Brasil. Nat Conser 14: 22-41.

CHAVE J ET AL. 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob Chang Biol 20: 3177-3190.

CHAVE J, COOMES D, JANSEN S, LEWIS SL, SWENSON NG & ZANNE AE. 2009. Towards a worldwide wood economics spectrum. Ecol Lett 12: 351-366.

CROUZEILLES R, CURRAN M, FERREIRA MS, LINDENMAYER DB, GRELLE CEV & REY BENAYAS JM. 2016. A global meta-analysis on the ecological drivers of forest restoration success. Nat Commun 7: 11666.

DOMÍNGUEZ-HAYDAR Y, VELÁSQUEZ E, CARMONA J, LAVELLE P, CHAVEZ LF & JIMÉNEZ JJ. 2019. Evaluation of reclamation success in an open-pit coal mine using integrated soil physical, chemical and biological quality indicators. Ecol Indic 103: 182-193.

FAITH DP. 2016. The PD Phylogenetic Diversity Framework: Linking Evolutionary History to Feature Diversity for Biodiversity Conservation. In: PELLENS R & GRANDCOLAS P (Eds), Biodiversity Conservation and Phylogenetic Systematics: Preserving our evolutionary heritage in an extinction crisis, Cham: Springer International Publishing, p. 39-56.

FOREST F ET AL. 2007. Preserving the evolutionary potential of floras in biodiversity hotspots. Nature 445: 757-760.

GANN GD ET AL. 2019. International principles and standards for the practice of ecological restoration. Second edition. Restor Ecol 27: S1-S46.

GASTAUER M, CALDEIRA CF, RAMOS SJ, SILVA DF & SIQUEIRA J. 2019b. Active rehabilitation of Amazonian sand mines converges soils, plant communities and environmental status to their predisturbance levels. Land Degrad Dev 31: 607-618.

GASTAUER M ET AL. 2020. Integrating environmental variables by multivariate ordination enables the reliable estimation of mineland rehabilitation status. J Environ Manage 256: 109894.

GASTAUER M & MEIRA-NETO JAA. 2017. Updated angiosperm family tree for analyzing phylogenetic diversity and community structure. Acta Bot Brasilica 31: 191-198.

GASTAUER M, NASCIMENTO JR WR, CALDEIRA CF, RAMOS SJ, SOUZA-FILHO PW & FÉRET JB. 2022. Spectral diversity allows remote detection of the rehabilitation status in an Amazonian iron mining complex. Int J Appl Earth Obs Geoinf 106: 102653.

GASTAUER M ET AL. 2021. Shannon tree diversity is a surrogate for mineland rehabilitation status. Ecol Indic 130: 108100.

GASTAUER ET AL. 2024. Large-scale forest restoration generates comprehensive biodiversity gains in an Amazonian mining site. J Clean Prod 443: 140959.

GASTAUER M, SILVA JR, CALDEIRA JUNIOR CF, RAMOS SJ, SOUZA FILHO PWM, FURTINI NETO AE & SIQUEIRA JO. 2018. Mine land rehabilitation: Modern ecological approaches for more sustainable mining. J Clean Prod 172: 1409-1422.

GASTAUER M, SOUZA FILHO PWM, RAMOS SJ, CALDEIRA CF, SILVA JR, SIQUEIRA JO & FURTINI NETO AE. 2019a. Mine land rehabilitation in Brazil: Goals and techniques in the context of legal requirements. Ambio 48: 74-88.

GELOT S & BIGARD C. 2021. Challenges to developing mitigation hierarchy policy: findings from a nationwide database analysis in France. Biol Conserv 263: 109343.

GIULIETTI AM ET AL. 2019. Edaphic Endemism in the Amazon: Vascular Plants of the canga of Carajás, Brazil. Bot Rev 85: 357-383.

GUEDES RS, RAMOS SJ, GASTAUER M, JÚNIOR CFC, MARTINS GC, DA ROCHA NASCIMENTO JÚNIOR W, DE SOUZA-FILHO PWM & SIQUEIRA JO. 2021. Challenges and potential approaches for soil recovery in iron open pit mines and waste piles. Environ Earth Sci 80: 640.

GUERRA A ET AL. 2020. Ecological restoration in Brazilian biomes: Identifying advances and gaps. For Ecol Manage 458: 117802.

HSIEH TC, MA KH & CHAO A. 2016. iNEXT: an R package for rarefaction and extrapolation of species diversity (Hill numbers). Methods Ecol Evol 7: 1451-1456.

KEMBEL SW, COWAN PD, HELMUS MR, CORNWELL WK, MORLON H, ACKERLY DD, BLOMBERG SP & WEBB CO. 2010. Picante: R tools for integrating phylogenies and ecology. Bioinformatics 26: 1463-1464.

KOLLMANN J ET AL. 2016. Integrating ecosystem functions into restoration ecology-recent advances and future directions. Restor Ecol 24: 722-730.

LAL R. 2009. Challenges and opportunities in soil organic matter research. Eur J Soil Sci 60: 158-169.

LALIBERTÉ E & LEGENDRE P. 2010. A distance-based framework for measuring functional diversity from multiple traits. Ecology 91: 299-305.

LAMB D, ERSKINE PD & FLETCHER A. 2015. Widening gap between expectations and practice in Australian minesite rehabilitation. Ecol Manage Restor 16: 186-195.

LECHNER AM, ARNOLD S, MCCAFFREY NB, GORDON A, ERSKINE PD, GILLESPIE MJ & MULLIGAN DR. 2018. Applying modern ecological methods for monitoring and modelling mine rehabilitation success. From Start to Finish – a Life-of-mine Perspective 3: 109-116.

LONDE V, SOUSA HCD & KOZOVITS AR. 2017. Key plant indicators for monitoring areas undergoing restoration: A case study at the Das Velhas River, southeast Brazil. Ecol Eng 103: 191-197.

MAGALLÓN S, GÓMEZ-ACEVEDO S, SÁNCHEZ-REYES LL & HERNÁNDEZ-HERNÁNDEZ T. 2015. A metacalibrated time-tree documents the early rise of flowering plant phylogenetic diversity. New Phytol 207: 437-453.

MARON M, BROWNLIE S, BULL JW, EVANS MC, VON HASE A, QUÉTIER F, WATSON JEM & GORDON A. 2018. The many meanings of no net loss in environmental policy. Nat Sustain 1: 19-27.

MAZÓN M, AGUIRRE N, ECHEVERRÍA C & ARONSON J. 2019. Monitoring attributes for ecological restoration in Latin America and the Caribbean region. Restor Ecol 27: 992-999.

MONTGOMERY DC, PECK EA & GEOFFREY VINING G. 2021. Introduction to Linear Regression Analysis, J Wiley & Sons, 704 p.

MUKHOPADHYAY S, MAITI SK & MASTO RE. 2014. Development of mine soil quality index (MSQI) for evaluation of reclamation success: A chronosequence study. Ecol Eng 71: 10-20.

OLIVER I, DORROUGH J & SEIDEL J. 2021. A new Vegetation Integrity metric for trading losses and gains in terrestrial biodiversity value. Ecol Indic 124: 107341.

PRACH K, DURIGAN G, FENNESSY S, OVERBECK GE, TOREZAN JM & MURPHY SD. 2019. A primer on choosing goals and indicators to evaluate ecological restoration success. Restor Ecol 27: 917-923.

R DEVELOPMENT CORE TEAM. 2020. R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing.

RAINEY HJ, POLLARD EHB, DUTSON G, EKSTROM JMM, LIVINGSTONE SR, TEMPLE HJ & PILGRIM JD. 2015. A review of corporate goals of No Net Loss and Net Positive Impact on biodiversity. Oryx 49: 232-238.

RIBEIRO RA, GIANNINI TC, GASTAUER M, AWADE M & SIQUEIRA JO. 2018. Topsoil application during the rehabilitation of a manganese tailing dam increases plant taxonomic, phylogenetic and functional diversity. J Environ Manage 227: 386-394.

ROSIÈRE CA & CHEMALE F JR. 2000. Brazilian Iron Formations and Their Geological Setting. Rev Bras Geociências 30: 274-278.

SER (Society for Ecological Restoration International Science & Policy Working Group). 2004. The SER international primer on ecological restoration. Society for Ecological Restoration International, Tucson. www.ser.org.

SERRA RT, SANTOS CD, ROUSSEAU GX, TRIANA SP, MUÑOZ GUTIÉRREZ JA & BURGOS GUERRERO JE. 2021. Fast recovery of soil macrofauna in regenerating forests of the Amazon. J Anim Ecol 90: 2094-2108.

TEIXEIRA PC, DONAGEMMA GK, FONTANA A & TEIXEIRA WG. 2017. Manual de métodos de análise de solo. Rio de Janeiro, Embrapa, 573 p.

TRINDADE FC, GASTAUER M, RAMOS SJ, CALDEIRA CF, ARAÚJO JF DE, OLIVEIRA G & VALADARES RB DA S. 2021. Soil Metaproteomics as a Tool for Environmental Monitoring of Minelands. For Trees Livelihoods 12: 1158.

VIANA PL ET AL. 2016. Flora das cangas da Serra dos Carajás, Pará, Brasil: história, área de estudos e metodologia. Rodriguésia 67: 1107-1124.

WORTLEY L, HERO J-M & HOWES M. 2013. Evaluating Ecological Restoration Success: A Review of the Literature. Restor Ecol 21: 537-543.

ZEIDE B. 1993. Analysis of Growth Equations. For Sci 39: 594-616.

How to cite
MEDEIROS-SARMENTO PS, CASTRO AF, PENNER FV & GASTAUER M. 2024. Indicators to quantify biodiversity gains for compensation and mineland rehabilitation in the Eastern Amazon. An Acad Bras Cienc 96: e20230236. DOI 10.1590/0001-3765202420230236.

Manuscript received on March 6, 2023;
accepted for publication on September 17, 2023

PRISCILA S. DE MEDEIROS-SARMENTO
https://orcid.org/0000-0002-5001-9573

ARIANNE F. DE CASTRO
https://orcid.org/0000-0002-9907-6667

FERNANDA V. PENNER
https://orcid.org/0000-0002-1106-6166

MARKUS GASTAUER
https://orcid.org/0000-0002-9599-0902

Instituto Tecnológico Vale, Rua Boaventura da Silva,
955, Nazaré, 66055-090 Belém, PA, Brazil

Correspondence to: **Markus Gastauer**
E-mail: markus.gastauer@itv.org

Author contributions

PSMS and MG: Substantial contribution to the concept and design of the study. Contribution to data collection. Contribution to the data analysis and interpretation. Contribution to manuscript preparation. AFC: Contribution to data collection. Contribution to manuscript preparation. FVP: Contribution to manuscript preparation.