Environmental and Sustainability Indicators 8 (2020) 100074

Contents lists available at ScienceDirect

Environmental and Sustainability Indicators

journal homepage: www.journals.elsevier.com/environmental-and-sustainability-indicators/

The sustainability index of the physical mining Environment in protected areas, Eastern Amazon

Pedro Walfir M. Souza-Filho [a,b,*], Rosane B.L. Cavalcante [a], Wilson R. Nascimento Jr. [a], Sâmia Nunes [a], Markus Gastauer [a,c], Diogo C. Santos [a], Renato O. Silva Jr. [a], Prafulla K. Sahoo [a,e], Gabriel Salomão [a], Marcio S. Silva [a], Silvio J. Ramos [a], Cecílio F. Caldeira [a], Roberto Dall'Agnol [a], José O. Siqueira [d]

[a] Instituto Tecnológico Vale, Belém, Pará, Brazil
[b] Geosciences Institute, Universidade Federal Do Pará, Belém, Pará, Brazil
[c] Post-Graduate Program in Ecology, Universidade Federal Do Pará, Belém, Pará, Brazil
[d] Soil Science Department, Universidade Federal de Lavras, Lavras, Minas Gerais, Brazil
[e] Department of Environmental Science and Technology, School of Environmental and Earth Science, Central University of Punjab, Bathinda, India

ARTICLE INFO

Keywords:
Carajás national forest
Environmental indicators
Sustainable mining
Protected areas
Indicators of sustainability

ABSTRACT

The application of sustainability principles to mining activities remains challenging. Explorations of non-renewable natural resources are irreversible; however, they can be better compensated for if the profit resulting from extraction is reinvested in social and human well-being and if environmental impacts are repaired. Thus, the evaluation of mining sustainability is necessary and requires efficient indicators to measure economic, social, and environmental performance. Here, we present the composite environmental sustainability index [CESI] of the landscape for iron mines in the Carajás National Forest, a protected site in the Brazilian Amazon. The index integrates 20 individual environmental indicators related to (1) changes in land cover and land use, (2) direct impacts caused by operations, (3) residue disposal and management, (4) energy, water, and soil resources, and (5) compensation for environmental damage. To define the threshold values for classifying individual indicators, we use legal requirements, data from the literature and historical time series. The values obtained for each of the individual indicators were normalized in terms of linguistic criteria, such as unsustainability (1), low sustainability (2) and high sustainability (3). The sustainability index of each of the five categories was calculated and based on these values, we computed the CESI of the physical mining environment. The values presented here represent baselines for further monitoring and evaluating the sustainability of the physical environment, guaranteeing iron ore exploitation in Carajás mining region with minimum environmental impacts. The proposed index can indicate a path towards environmental sustainability, especially in protected areas.

1. Introduction

In the publication "The Limits to Growth", the Club of Rome first revealed to society concerns about reconciling long-term economic growth and efficient protection of the environment and natural resources (Meadows, 1972). Ten years later, the concept of sustainability officially emerged in the World Charter for Nature (UN, 1982), which expressed the apprehensions of environmentalists regarding the future of the planet at the zenith of industrial development. The Brundtland Report entitled "Our Common Future" (Brundtland, 1987) defined sustainability as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". In 2015, the United Nations (UN) and the Paris Agreement on Climate Change adopted the 2030 Agenda for Sustainable Development, with its 17 sustainable development goals (SDGs). These agreements aimed to reduce poverty and spur economic growth while tackling climate change and preserving oceans and forests.

Many sustainable development indicators (SDIs) have been defined to measure the progress of the mining industry in relation to the SDGs (Hák et al., 2016); however, the application of sustainability principles to mining activities remains challenging (Gorman and Dzombak, 2018). The reason is that mining represents the act of removing and consuming

---

* Corresponding author. Instituto Tecnológico Vale. Belém, Pará, Brazil.
E-mail addresses: walfir@ufpa.br, pedro.martins.souza@itv.org (P.W.M. Souza-Filho).

https://doi.org/10.1016/j.indic.2020.100074
Received 30 April 2020; Received in revised form 25 August 2020; Accepted 28 September 2020
Available online 30 September 2020

limited resources, which is incompatible with the vision of sustainability in (Brundtland, 1987). To overcome this irreversible loss, the profit resulting from extraction needs to be reinvested in social and human well-being, and environmental impacts must be repaired. Therefore, recent definitions consider sustainability at the intersection of the social, economic, and environmental spheres, making development possible (economic-environmental), equitable (economic-social), and viable (environmental-social) (UN, 2012).

Thus, it is necessary to minimize environmental impacts achieve mining sustainability (Gastauer et al., 2018). To that end, mining operations adopt no net loss policies (Gastauer et al., 2012) as proposed by the mitigation hierarchy, which requires avoiding and minimizing unnecessary impacts (mitigation), repairing unavoidable impacts (reclamation, rehabilitation or restoration) and offsetting unrepairable impacts (compensation) (Arlidge et al., 2018). Several organizations, such as the International Council on Mining and Metals (ICMM, 2006) and the Global Reporting Initiative (GRI, 2013), as well as SDGs in mining (Sonesson et al., 2016) have emerged to guide the transition of the sector towards sustainability. These initiatives increase the benefits and competitive advantage of all enterprises that adopt the SDGs in their operations, highlighting the awareness in the mining industry that the exploitation of natural resources must not occur at the expense of environmental, social, or economic intactness. Therefore, mining companies have collaborated with government sectors to conserve protected areas and with civil society organizations to support the provision of collective goods (Martins and Mendonça, 2014). The emerging sustainability departments in many companies have shifted the idea of sustainability to the centre of the mining business in the 21st century (Mudd, 2010). Hence, the mining industry has an unprecedented opportunity to mobilize societal, physical, technological and financial resources to advance towards meeting the SDGs (Sonesson et al., 2016).

However, SDIs must be selected, revisited and refined based on a coherent framework (Singh et al., 2012) because the dimensions of sustainable development (SD) are almost immensurable (Böhringer and Jochem, 2007). To become a more powerful process and to satisfy fundamental scientific requirements, it is necessary to assess this question based on three central steps of index definition: normalization to make data comparable, weighting to specify the correct interrelationships, and aggregation to obtain the right functional relationship (Nardo et al., 2005). Even when maintaining this scientific rigor, the choice of variables, normalization methods and weightings will generally be related to subjective judgements, in contrast to meaningful aggregation methods for these variables, without normalization (Ebert and Welsch, 2004).

Evaluating mining sustainability requires efficient and measurable indicators for measuring the individual economic, social, and environmental performance of a mining company to provide information on how it contributes to SD (Azapagic, 2004). There are several initiatives for establishing quantitative indicators for measuring the sustainability of

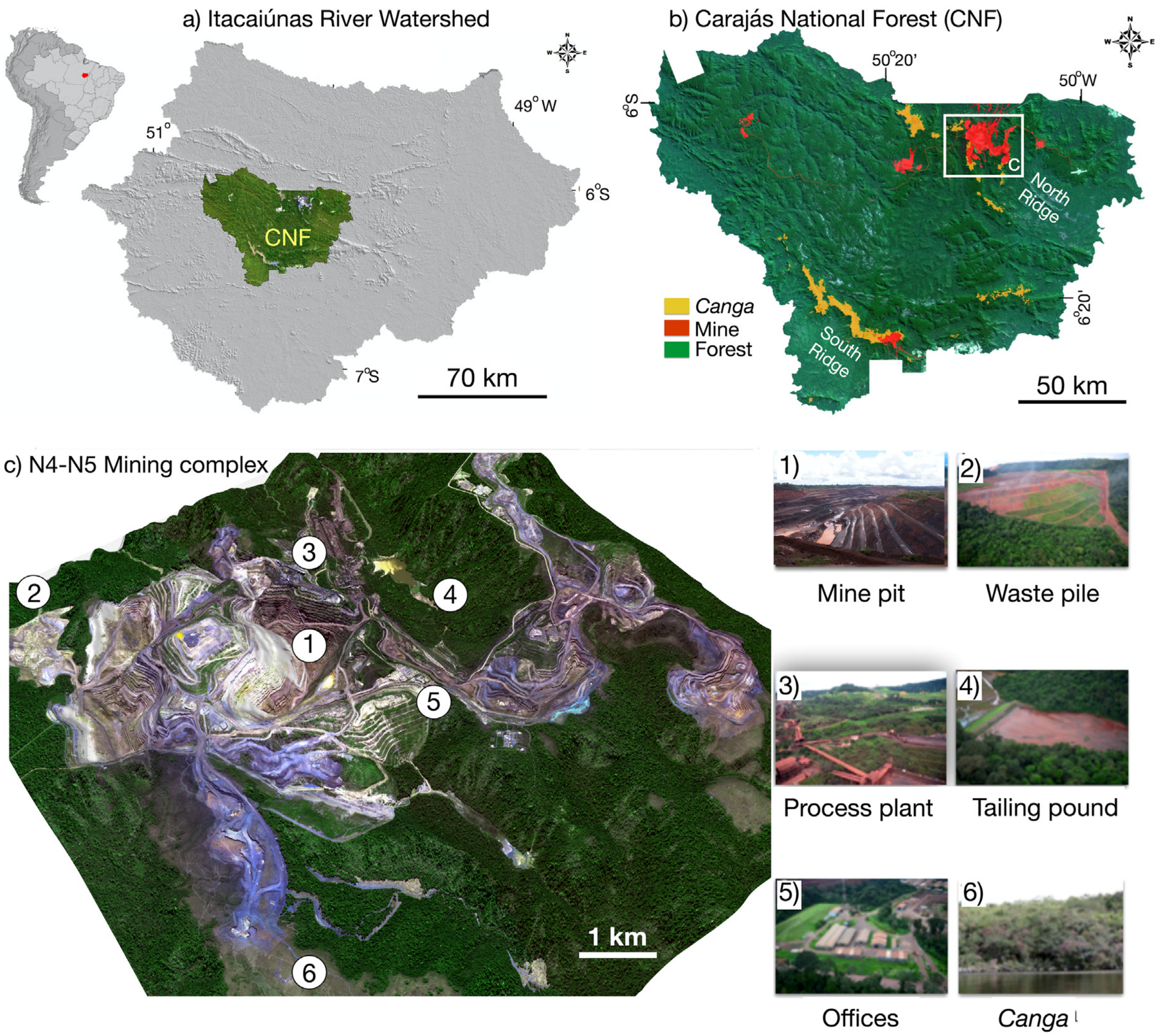

Fig. 1. Location map of the study area. A) Itacaiúnas River basin (IRB). B) Land cover and land use map of the Carajás National Forest (CNF). C) Details of the N4-N5 iron mining complex.

mining activity, whether on a national scale (Dialga, 2018; Zvarivadza, 2018) or on a local scale (Marnika et al., 2015; Worrall et al., 2009).

In this study, we aim to measure the sustainability of the physical environment of iron ore mining operations in the Carajás National Forest (CNF), a protected area in the eastern Amazon, Brazil, to quantify the general impacts of such operations. We focus on the physical environment given the availability of indicators obtained by remote sensing approaches or additional data that are usually surveyed to address environmental liability. From the perspective of SD in mining, we develop the composite environmental sustainability index [CESI] of the physical mining environment, composed of indicators related to (i) changes in land cover and land use, (ii) direct impacts caused by mining operations, (iii) residue disposal and management, (iv) energy, water and soil resources, and (v) compensation for environmental damage. This index is designed as a baseline for ongoing mining activities in the region (Mota et al., 2017), enabling further comparison with mining operations from more distant regions and application to similar projects, especially in protected areas.

2. Materials and methods

2.1. Study site

This study was conducted out in the world's largest opencast iron ore mines, situated in the CNF, a protected area in the eastern Amazon, Brazil (Fig. 1). Considering the geological and environmental specificities of the CNF, the management plan of this protected area allows mining activities despite its protection status, as in 33 additional protected areas of sustainable use in the Brazilian Amazon (Ricardo and Rolla, 2006). Protected areas encompass 28% of the area of the Amazon biome and have an important role in reducing Amazon deforestation (Soares Filho, 2016), although their contribution to the total deforestation of the Amazon had recently increased (Araújo et al., 2017).

The CNF is located in the Itacaiúnas River basin (IRB) and accommodates the world's largest reserves of high-grade iron ore. The IRB occupies an area of 41,300 km^2 (Fig. 1a), of which 51% has already been deforested; 70% of the remaining forest areas are located inside a mosaic of protected areas and indigenous areas (Souza-Filho et al., 2016). The main cause of deforestation is cattle raising. The iron mining activities occurring in the CNF (Fig. 1b) are responsible for changes in land cover and land use, and natural vegetation formations have been suppressed (Souza-Filho et al., 2019), including evergreen or semi-deciduous forests and the *Amazonian canga* of Carajás (Devecchi et al., 2020). The surface of the land is remodelled for the construction of mining infrastructure, such as tailings ponds, mine pits, waste piles, access roads, offices, and even urban centres (Fig. 1c). To regulate mining and further economic activities, the management plan of the CNF (MPCNF) establishes zones for mining, different forms of extractive activities and conservation (Gonçalves, 2016a, b).

The mining areas are inserted in the context of the dissected plateau carved out of Archean rocks (Grainger et al., 2008), known in the region as Serra dos Carajás (Carajás Ridge). The Carajás Plateau is located in the centre of the Itacaiúnas watershed (IRW) (Fig. 1a), and its main segments are the North and South Ridges (Fig. 1b). The tops of plateaus feature laterites, haematite breccia and conglomerates that occur at elevations ranging from 500 m to 904 m (Piló et al., 2015). Iron ore mining projects started in the early 1980s on the North Ridge (Tolbert et al., 1971), when the iron ore N4-N5 mining complex was established (Fig. 1c). Therefore, a mining activities plan was defined in the Carajás region almost 20 years before the creation of the CNF. Compared to the original mining plan, the MPCNF restricted the mining area. At the same time, the main iron ore targets were kept as mining sites (Gonçalves, 2016a).

2.2. Individual indicators for assessing the sustainability of the physical mining environment

Azapagic et al. (2004), Marnika et al. (2015) and the GRI (2013) have proposed different categories of indicators for the mining and minerals industry. In this paper, we selected five aspects of the physical environment related to iron ore mining activities in CNF protected areas for evaluation: (1) changes in land cover and land use, (2) direct impacts caused by mining operations, (3) residue disposal and management, (4) energy, water, and soil resources, and (5) compensation for environmental impacts.

The environmental indicators were defined basically from four criteria: the selection of SDIs tried to reflect the entire holistic nature of

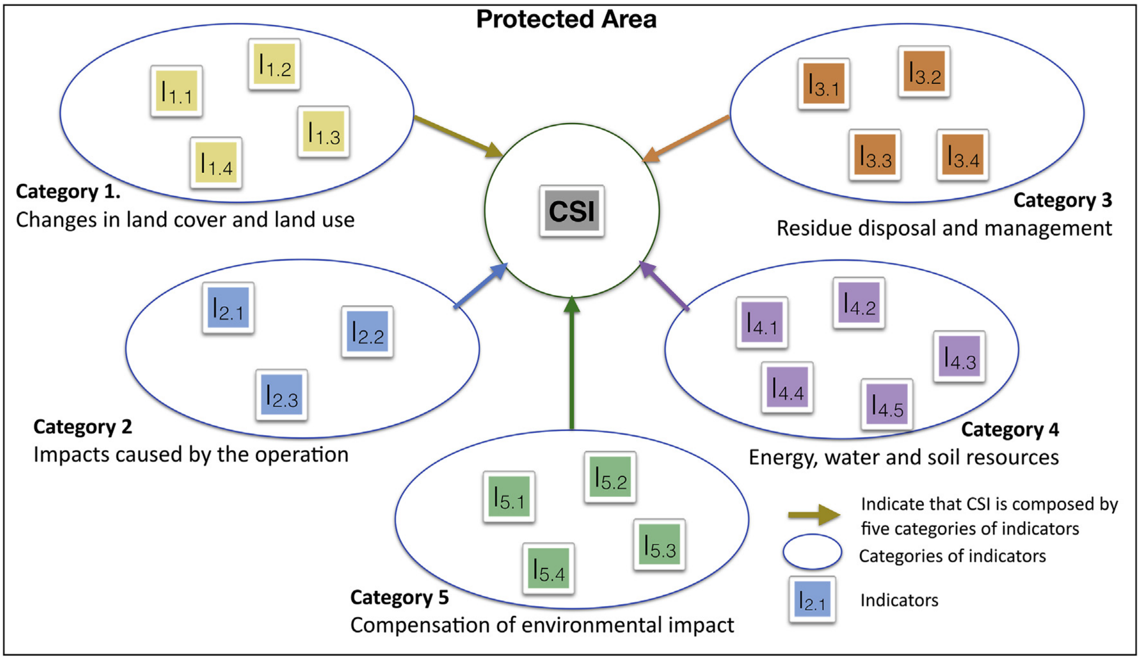

Fig. 2. Theoretical framework for the construction of the composite environmental sustainability index [CESI] of the physical mining environment (adapted from (Dialga, 2018)).

Table 1

Definition, importance, computation reference and threshold values for 20 indicators used to assess sustainability of the physical mining environment. HS has high sustainability, LS has low sustainability, and the US is an unsustainable mining practice. (3), (2), and (1) are normalized values for sustainability status. CNF is the Carajás National Forest (Gonçalves, 2016a, 2016b), US is unsustainable, MS is moderate sustainability, and HS is high sustainability.

Indicator	Definition	Equation	Parameter(s)	HS (3)	LS (2)	US (1)	Data source and sample size
1. Changes in land cover and land use							
I1.1	Percentage of deforested area in CNF	$\frac{A_d}{A_{CNF}} \cdot 100$	Ad: deforested area within CNF [km2], A_{CNF}: area of CNF [km2]	<10.3%	10.3–20.5%	>20.5%	Souza-Filho et al. (2018), 2017 satellite image
$I_{1.2}$	Percentage of deforested area for mining activities in CNF	$\frac{A_m}{A_{CNF}} \cdot 100$	A_m: total mine area [km^2] A_{CNF}: area of CNF [km^2]	<7.0%	7.0–14.0%	>14.0%	Souza-Filho et al. (2018), 2017 satellite image
$I_{1.3}$	Density of native vegetation fragments in the landscape	$\frac{N_f}{A_{CNF}}$	N_f: number of vegetation fragments, A_p: protected area [km^2]	<0.01	0.01–0.10	>0.10	Souza-Filho et al. (2018), 2017 satellite image
$I_{1.4}$	Density of roads within the CNF	$\frac{L_r}{A_{CNF}}$	L_r: extension of roads, A_p: protected area [km^2]	<0.06	0.06–0.37	>0.37	Souza-Filho et al. (2018), 2017 satellite image
2. Impacts caused by operation							
$I_{2.1}$	Particle emission	–	Mean annual suspended particle emission [μg/m^3]	<60 μg/m^3	60–80 μg/m^3	>80 μg/m^3	Vale (unpublished data); annual monthly average (2017)
$I_{2.2}$	Distance between mining sites and communities	–	Minimum distance between mining site and urban areas [km]	>0.45 km	0.11–0.45 km	<0.11 km	Souza-Filho et al. (2018), 2017 satellite image
$I_{2.3}$	Visibility of mining sites from settlements and cities	–	Visibility of mining sites	Not visible	Little visible	Highly visible	Field survey in 2017
3. Residue disposal and management							
$I_{3.1}$	Stripping ratio (ratio between waste and iron ore)	$\frac{V_w}{V_m}$	V_w: volume of waste deposited, V_m: volume of mined ore	<0.57	0.57–0.98	>0.98	Vale (unpublished data); annual monthly average (2017)
$I_{3.2}$	Risk assessment of tailing dams	–	Brazilian dam classification due to associated potential damage (maximum value for the facilities inside CNF)	No or small tailings, tailings with low risk	Higher risk is moderate	Higher risk is high	DNPM (2017)
$I_{3.3}$	Potential damage from tailing breaks	–	Brazilian dam classification of associated potential damage of dam break. CNRH n. 143 de 2012 e DNPM 70389 de 2017.	No or small tailings, tailings with low potential damage	Higher potential damage is moderate	Higher potential damage is high	DNPM (2017)
$I_{3.4}$	Ratio of plant gross mine production	$\frac{P_g}{P_{rom}}$	P_g: gross production of processing plant P_{rom}: mine production (run of mine)	>0.9	0.7–0.9	>0.7	Vale (unpublished data); annual monthly average (2017)
4. Resource efficiency							
$I_{4.1}$	Total energy consumption per produced unit of ore	$\frac{E}{P_m}$	E: energy consumption (MWh), P_m: annual iron ore production (Mton)	<2500 MWh/Mton	2500-3000 MWh/Mton	>3000 MWh/Mton	Vale (unpublished data); annual monthly average (2017)
$I_{4.3}$	Percentage of reused water in the mining process	$\frac{W_r}{W_r + W_w} \cdot 100$	W_r: reused, recycled, and use of drainage water W_w: annual catchment of new water	>66%	33–66%	<33%	Vale (unpublished data); annual monthly average (2017)
$I_{4.4}$	Water quality index	–	Percentage of creeks and rivers with good or excellent water quality	>90%	70–90%	<70%	Sahoo et al. (2019), 2017 field survey
$I_{4.5}$	Soil quality index	–	Percentage of soils samples with high or excellent soil quality	>90%	70–90%	<70%	Sahoo et al. (2020), 2017 field survey
5. Compensation of environmental impacts							
$I_{5.1}$	Compensation of deforestation by restoration outside CNF	$\frac{A_{ref}}{A_d}$	A_{ref}: reforested areas outside CNF (km^2), A_d: deforested areas within CNF (km^2)	>2	2-1	<1	Souza-Filho et al. (2018), 2017 satellite image
$I_{5.2}$	Compensation of deforestation by protected areas outside CNF	$\frac{A_p}{A_d}$	A_p: permanently protected areas outside CNF due to environmental compensation (km^2), A_d: deforested areas within CNF (km^2)	>2	2-1	<1	Souza-Filho et al. (2018), 2017 satellite image
$I_{5.3}$	Carbon balance	$E_{CO2} - S_{CO2}$	E_{CO2}: CO_2 emissions by operation (Mton), S_{CO2}: CO_2 sequestration in revegetated areas (Mton)	≤0	–	>0	Vale (unpublished data); annual monthly average (2017)
$I_{5.4}$	Percentage of revegetated mine land	$\frac{A_{rev}}{A_m} \cdot 100$	A_{rev}: revegetated areas in the mine, A_m: mine area	<5%	5–20%	>20%	Souza-Filho et al. (2018), 2017 satellite image

the sustainability of the physical mining, data availability and use, the spatial and temporal scales, and the possibility of indicator aggregation. Hence, twenty indicators were retrieved from primary data (collected in the field or from the interpretation of satellite images) and secondary data (reports and national statistics) for 2017 to provide the CESI of the physical mining environment in Carajás iron ore mines. We defined 2017 as the baseline reference for comparison of future mining activities in the region due to the revision of the MPCNF that occurred in 2016. In this document, the Brazilian Institute for Environment established new legal milestones for mining inside the CNF (Gonçalves, 2016a, b). All of our indicators were defined in terms of contiguous geography based on local (e.g., mining sites in the context of the CNF) and regional spatial scales (e.g., the CNF in the context of the IRB).

It is necessary to normalize individual indicators to construct composite indices (Dialga, 2019), with the aim of standardizing the units of measurement of individual indicators to allow integration in the next step. We used three categorical scales (scored from 1 to 3) to normalize the indicators, as indicated in Table 1. Because most of the indicators vary widely for each commodity, the thresholds of each category were established according to regulatory frameworks such as the MPCNF (Gonçalves, 2016a, b), scientific articles (Marnika et al., 2015; Salomão et al., 2018), and historical data series or in comparison with the average values for protected and non-protected areas in the region (Table 1). The values obtained for each of the individual indicators were normalized in terms of linguistic criteria, such as unsustainability (1), low sustainability (2) and high sustainability (3). The sustainability index of each of the five categories was calculated as the geometric mean of the normalized values of their indicators, considering equivalent weighting since there are no statistical or empirical grounds to recognize different statuses of the indicators. Based on these values, we computed the CESI of the physical mining environment as the geometric mean value from the aggregation of the five categories.

Therefore, this model is based on a top-down methodology, where all indicators and their threshold values, normalization, weighting and aggregation were defined by academics, without consulting stakeholders from the corporate and operational divisions of mining companies or the affected civil society. Fig. 2 presents the framework of the five categories of environmental indicators used to construct the CESI. The full list of categories, the individual environmental indicators, the definitions, equations, parameters, and rules of indicator normalization and the data source are presented in Table 1.

Group 1. Changes in land cover and land use

Changes in land cover and land use reflect the interaction between economic development and biodiversity conservation (Tesfaw et al., 2018). Habitat loss and fragmentation are widely recognized as a major cause of biodiversity loss (Groombridge, 1992). In addition to direct habitat loss, deforestation can cause alterations in climate, water balance and other disturbances (Souza-Filho et al., 2016), with a loss of ecosystem services (Ellison et al., 2017). Indicators I1.1 and I1.2 represent the total deforestation in the preserved area and the deforestation for mining facility installation, respectively. Under the MPCNF, 20.5% of this protected area consists of zones where human activities can be developed, and 14% consists of zones reserved for mining activities (Gonçalves, 2016a, b). These percentages were used as the thresholds between low sustainability and unsustainability. These indicators were classified as high sustainability if less than half of the land cover alteration predicted in the MPCNF was already achieved. Importantly, even before the creation of the CNF in 1998, the main sustainable use in this protected area has been related to mining activity (Martins and Mendonça, 2014).

Indicator I1.3 is an index of forest fragmentation that measures the disruption of landscape continuity, increasing border effects and the degree of isolation between populations (Metzger, 2003). The threshold

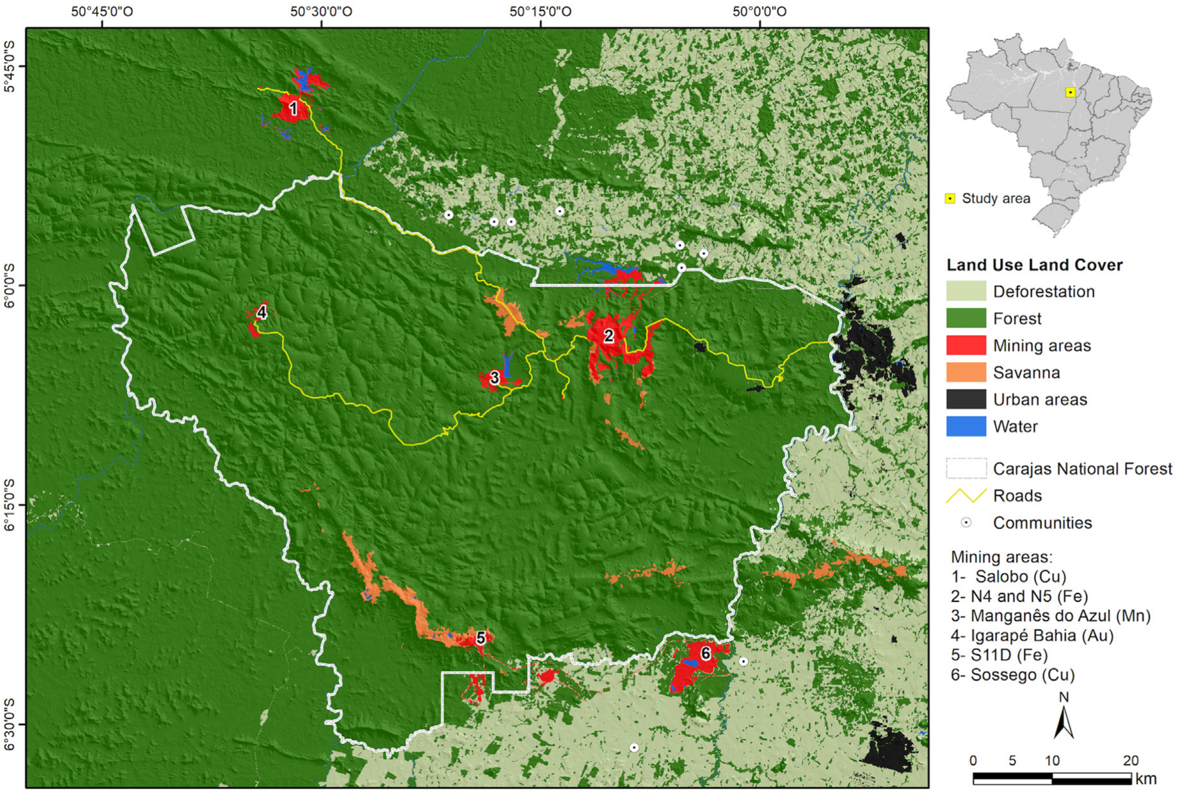

Fig. 3. LULC classification and mining dams inside the CNF. Roads, railways, protected areas and communities are presented in the map of the Itacaiúnas River basin (IRB). Cu = copper, Fe = iron, Mn = manganese, and Au = gold. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

values of the classes were determined in this study, considering a single fragment as high sustainability.

An indicator of road density inside the protected area was used (I1.4) because roads generate edge effects beyond deforestation and fragmentation, with increased susceptibility to external disturbances and impacts on the microclimate, fauna and flora (Barber et al., 2014). Road density was classified as high sustainability if the road density was lower than the average value for all protected areas situated in the IRB (0.06 km/km^2). However, it was classified as unsustainable if the road density was higher than the average value for the entire IRB (0.37 km/km^2). Notably, in other protected areas adjacent to the CNF, road density is associated with other types of land use, such as illegal logging and pastureland expansion. Hence, this indicator allowed us to compare the impact of different land uses in distinct protected areas of sustainable use.

The forest and deforested areas inside the CNF and reference regions were obtained using the land use/land cover (LULC) classification (Fig. 3) for the IRB (Souza-Filho et al., 2018). The extension of roads was manually digitalized from the Quantum GIS (QGIS) measured from 2017 Sentinel-2A satellite images.

Group 2. Impacts caused by operations

Indicator 2.1 is expressed as the number of total suspended particles (PTS) originating from mining activities. It indirectly evaluates the effectiveness of the measures adopted to reduce suspended particles. The reference values of the sustainability classes are the primary (concentrations of pollutants that in the long term may affect the health of the population) and secondary (concentrations of pollutants below which a minimum adverse effect on population well-being is predicted, as well as minimal damage to fauna and flora) standards of air quality established by National Environmental Council (CONAMA) Resolution 003/1990 (80 and 60 μg/m^3, respectively). Mining companies provided the PTS data series.

The shortest distance between a mining area within the CNF and a human settlement or city outside the CNF (Indicator I2.2) was calculated using a 3D digital elevation model and LULC classification (Fig. 3). The limits of each class were defined based on Marnika et al. (2015).

Indicator 2.3 assesses whether the mining areas are visible to the surrounding communities. This indicator was included to consider the visual perception of the landscape and the impact on the aesthetic value of the forest (Svobodova et al., 2012) and cultural and traditional landscapes (Jones, 2003). To measure and investigate the visual perception of mining sites by neighbouring communities, we used a 3D visualization model of the landscape to measure the distance from the mining sites to nearby communities. Furthermore, we checked in the field if it was possible to view mining structures from different human settlements and cities.

Group 3. Residue disposal and management

Depending on the depth of iron ore deposits and their geological composition, extraction generates different amounts of waste. Mining wastes or overburdens are waste rock overlying ore or mineral bodies. Tailings emerge due to the separation of the fraction of valuable mineral from the fraction of ore without economic value. The indicators in this group include the stripping ratio, i.e., the ratio between waste and produced iron ore (I3.1); the risk assessment of tailing dams (I3.2) and the potential damage from tailing breaks (I3.3); and the ratio of plant gross mine production (I3.4). Vale S.A. (unpublished data) provided all information about mine and waste production for this study. Importantly, that the ratios of I3.1 and I3.4 fall over the years, while the classification of the risk and (I3.2) and the potential damage from tailing breaks (I3.3) is defined by the Brazilian Mining Agency.

The 20th (0.57) and 80th (0.98) percentiles of the series of available annual data on waste production between 1986 and 2019 were used as thresholds for indicator I3.1. For indicator I3.4, we used the ratio of plant gross mine production in the year preceding the year of analysis as a reference (0.9 in 2016). An increase in the ratio was classified as high sustainability. Mining companies provided both data series.

The classes of tailing dam risk assessment (I3.2 and I3.3) were determined considering the Brazilian dam classification (DNPM 70,389/2017). Mining dams are classified according to the risk category (RC) as high, moderate, or low, and this classification considers the technical characteristics of dams, their conservation status and the dam safety plan; additionally, the associated potential damage (APD) is classified as high, moderate, or low. For the analysis, we considered the highest risk among all mining dams within the CNF included in the national dam registry. The dams and their classifications are available at http://www.anm.gov.br/assuntos/barragens/arquivos-barragens. We classified an area as having high sustainability if there is no dam; therefore, dams not included in the National Dam Safety Plan are not classified due to their small size or low RC/APD. If the highest RC/APD is moderate (high), an area is considered to have low sustainability (unsustainability).

Group 4. Resource efficiency

The indicators related to energy and water use efficiency, water reuse, and water and soil quality are grouped in this category. The total energy consumption per produced unit of ore was used as an indicator (I4.1) for energy use efficiency and energy-saving practices. The reference adopted is the value obtained in the reference year (2500 MWh/Mton in 2016). A decrease in energy use efficiency was classified as high sustainability.

The excessive use of water resources and pollution of such resources can affect the functioning of ecosystems and downstream water availability, which can have impacts on the quality of social and economic life. Measures of the use of new water in the ore production process per unit ore produced (I4.2) and the percentage of reused water (I4.3) in the mining process were chosen as indicators of sustainable water use. Reuse is a sustainable alternative for water supply, as the process reduces the withdrawal of new water from the environment and reduces the volume of generated effluent; the process also serves as a local control and reduces the impact of the construction of a new supply structure. The reference values for 2016 (I4.2 = 0.093 Mm^3/Mton and I4.3 = 66%) were used as limits for the high sustainability class, aiming at the continuous improvement of water use efficiency. Vale S.A. (unpublished data) provided the values related to indicators G4-EN8 and G4-EN10 of the GRI Sustainability Reporting Guidelines.

The water and soil quality indices are expressed as the percentage of water and soil samples in the studied area. Good or excellent quality was associated with the maximum and minimum limits of several quality parameters indicated in regulatory standards. Soil quality reflects the capacity to sustain biological productivity, environmental quality, and plant and animal health (Karlen et al., 1997). The quality of water bodies is determined by the interaction of water with the land use, land cover, soils, and geology of the catchment area. We used the quality classification of a broad analysis of soil and water bodies in the region (Sahoo et al., 2019, 2020b). We compared the values of the water quality parameters with the threshold values (CONAMA Resolution 357/2005). Additionally, the values of the soil quality parameters were compared with the threshold values (CONAMA Resolution 460/2013). We classified these indicators as high sustainability if more than 90% of the samples were classified as good or excellent.

Group 5. Compensation for environmental impacts

Mining activities cause logging and vegetation suppression that must be compensated for by either restoring degraded areas or protecting undisturbed vegetation (e.g., forest and *canga* vegetation) outside the mining area. The restoration and protection areas are determined in the environmental license of a mining project. For example, as of 2016, the CNF had lost nearly 20% of its original Amazonian *canga* vegetation (Souza-Filho et al., 2019) due to mining activities. However, 21% of the *canga* area in the Carajás Mineral Province is currently protected due to the creation of the Campos Ferruginosos National Park (Souza-Filho et al., 2019).

This group of indicators refers to the extent to which the deforested area in the CNF was compensated for through both the restoration and

Table 2
Values and sustainability class of each indicator.

Indicator	Definition	Value	Sustainability class
1. Changes in land cover and land use (2.71)			
$I_{1.1}$	Percentage of deforested area in CNF	2.30%	High (3)
$I_{1.2}$	Percentage of deforested area for mining activities in CNF	1.8%,	High (3)
$I_{1.3}$	Density of native vegetation fragments in the landscape	0*	High (3)
$I_{1.4}$	Density of roads within the CNF	0.1	Low (2)
2. Impacts caused by operation (3.00)			
$I_{2.1}$	Particle emission	29.7 $\mu g/m^3$	High (3)
$I_{2.2}$	Distance between mining sites and communities	2.6 km	High (3)
$I_{2.3}$	Visibility of mining sites from settlements and cities	Not visible	High (3)
3. Residue disposal and management (2.45)			
$I_{3.1}$	Ration between waste and iron ore	0.4	High (3)
$I_{3.2}$	Risk assessment of tailing dams	High APD	Low (2)
$I_{3.3}$	Potential damage of tailing dams	High APD	Low (2)
$I_{3.4}$	Ratio of plant gross mine production	0.95	High (3)
4. Resource efficiency (2.55)			
$I_{4.1}$	Total energy consumption per produced unit of ore	2954.7 MWh/Mton	Low (2)
$I_{4.2}$	Water withdraw per unit ore production	0.091	High (3)
$I_{4.3}$	Percentage of reused water in the mining process	62.60%	Low (2)
$I_{4.4}$	Water quality index	94.90%	High (3)
$I_{4.5}$	Soil quality index	99.20%	High (3)
5. Compensation of environmental impacts (2.45)			
$I_{5.1}$	Compensation of deforestation by restoration outside CNF	3.7	High (3)
$I_{5.2}$	Compensation of deforestation by protected areas outside CNF	26.4	High (3)
$I_{5.3}$	Carbon balance	434 Mton	Low (2)
$I_{5.4}$	Percentage of revegetated mine land	19%	Low (2)

protection of native vegetation (Table 1). Indicator $I_{5.1}$ provides the proportion of deforestation within the CNF that was compensated for through restoration outside the area, while indicator $I_{5.2}$ defines the proportion of deforestation within the CNF that was compensated for by protecting native vegetation outside the area. The proportion of the compensated area is based on the MPCNF (Gonçalves, 2016a), and its location is established by the Brazilian Forest Code (Brancalion et al., 2016). In general, compensation is carried out as closely as possible to the degraded area in the IRW. We classified both indicators as high sustainability when the restored plus protected area was twice the size of the deforested area. The indicators were classified as unsustainability when the area that was restored or protected was less than the area that was deforested.

Further environmental impacts result from carbon emissions. However, CO_2 can be sequestered by revegetation and reforestation. Indicator $I_{5.3}$ indicates a positive carbon balance with higher sustainability, while a negative carbon balance indicates higher emissions than sequestration, which is classified as unsustainability.

Indicator $I_{5.4}$ depicted the proportion of the total mining area that was reforested. The deforested area, the reforested area in the mine and the mining area were obtained using the LULC classification for the IRB (Souza-Filho et al., 2018). Mining companies provided the reforested area outside the CNF, the protected area outside the CNF and the carbon emissions and sequestration under the three scopes defined by the greenhouse gas protocol, assuming that the IRW is the best place for forest restoration.

3. Results

We found that 14 out of the 20 individual indicators show that the abiotic environment of Carajás iron ore mining operations is characterized by high sustainability, while six indicators show low sustainability (Table 2). The direct impacts on the physical environment caused by operations indicate complete sustainability of Carajás iron mining sites (Fig. 3), but the mean scores for other categories are lower.

Category 1, related to changes in land cover and land use, obtained a composite index value of 2.71 (on a scale of one to three) because the road density in the protected CNF (0.09 km/km^2) is higher than that in protected areas farther from the region, resulting in a slight penalty to indicator $I_{1.4}$ (low sustainability). The other indicators in this group were classified as high sustainability since 91 km^2 of the total area of the CNF (3954 km^2) was deforested, 72 km^2 was deforested for mining activities, and the forest areas were grouped in just one fragment.

Category 2 had the maximum value because the PTS registered by air quality monitoring was lower than the primary standard defined by CONAMA; the nearest distance between a community and a mine inside the CNF was 2.6 km (Fig. 3), and the mines are not visible by any community.

The residue disposal category obtained a composite index of 2.45, as only three out of five individual indicators were evaluated as showing high sustainability. There are eleven mining dams inside the protected area inserted in the National Dam Safety Plan, two of which are on the border of the CNF and have a total volume of 151.7 Mm^3. Their risk and damage classification vary from E to B. However, due to the high APD of 5 dams, the indicator was classified as low sustainability.

The resource use efficiency category obtained a composite index of 2.55, as two out of five individual indicators were evaluated as showing moderate sustainability. Compared to previous years, the production of ore in 2017 presented a higher new water use efficiency, resulting in high sustainability for I4.2 but a slightly lower energy use efficiency and lower water reuse, resulting in low sustainability for I4.1 and I4.3.

Furthermore, reforestation efforts (I5.3) were associated with moderate sustainability of the indicator's compensation for CO_2 emissions, and mine land revegetation (I5.4) reduced the composite index achieved by compensation for the environmental impact category (score 2.45, Fig. 3). Indicators I5.1 and I5.3 achieved higher scores because the reforested (332 km^2) and protected (2395 km^2) areas outside the CNF, used to compensate for the deforestation of permanent preservation areas (Federal Law 9433/1997) inside the CNF, were, respectively, 3.7 and 26.4 times greater than the deforested area inside the conservation unit.

The CESI of the physical mining environment obtains a value of 2.62 for the iron ore mining activities in the CNF (Fig. 4).

4. Discussion

4.1. Assessing the sustainability of mining activities in the CNF

The CESI of the physical mining environment indicates the sustainability of iron ore mining enterprises in the CNF. Under the supervision of independent environmental agencies, such as the Brazilian Institute of the Environment (IBAMA) and the Chico Mendes Institute for Biodiversity (ICMBio), all legal requirements regarding mining in the CNF are met or even outperformed by the mining companies. This includes logging and mining activities as well as the permanent and temporary rehabilitation of mine lands. Compared to the baseline established in 2016, the majority of soil and water samples inside the CNF have good or excellent quality compared to the legal standards (Sahoo et al., 2019, 2020a; Salomão et al., 2020).

Although the overall sustainability of the physical environment of actual Carajás mining operations has been revealed in this study, some individual indicators show that the iron mines examined are

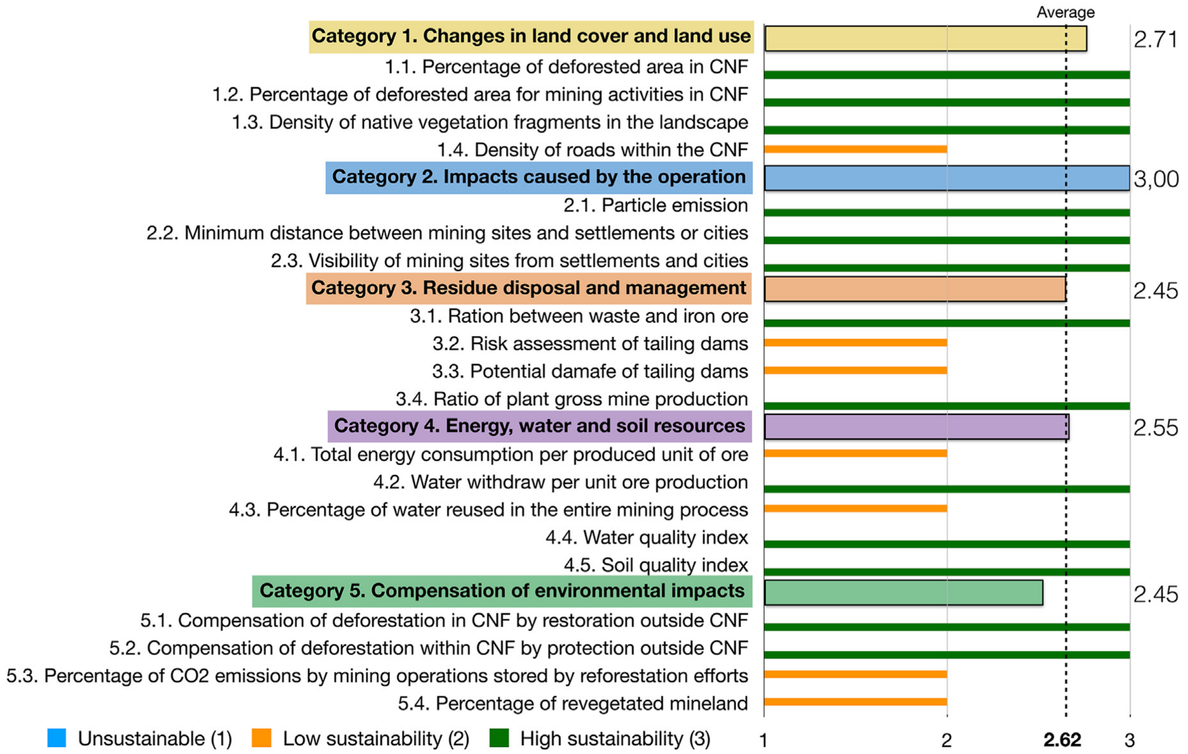

Fig. 4. Normalization of individual indicators and categories used to compute the composite environmental sustainability index [CESI] of the physical mining environment for the Carajás National Forest. The dashed line indicates the value of the index.

characterized by low sustainability. To increase the sustainability of the abiotic environment of Carajás iron ore mining operations, activities should focus on the individual indices that show low sustainability.

4.2. Recommendations to increase sustainability in mining activities

Some indicators such as the indicator of road density within the CNF are alarming, as studies note that road construction is one of the main vectors of deforestation in protected areas in the Amazon (Barber et al., 2014). The roads are mostly related to mining activity, and the Vale S.A. mining company provides technological support for monitoring the conservation unit in partnership with the Brazilian government to prevent illegal deforestation. However, roads generally promote disturbances to local soils and hydrology and can represent sources of chemical pollutants; roads can also generate edge-related changes in the forest structure, microclimate and forest dynamics, among other impacts (Laurance et al., 2009). Therefore, the construction of new roads should be avoided.

The total volume of solid residue, i.e., tailings and mining wastes, should be reduced to increase the sustainability of this indicator. The relative mining waste produced is expected to decrease over the lifetime of a mine. Therefore, the actual expansion of the mines in the N4-N5 complex may have contributed to this evaluation. Furthermore, the start of mining activities in S11D, characterized by near-surface iron ore deposits, is expected to contribute to the better performance of this indicator. Ongoing studies are evaluating the possibility of reusing tailings, which may contribute to a reduction in the residue-ore ratio.

Finally, the tailing dams inside the CNF were classified as low sustainability due to their high potential to damage the environment and socio-economic activities, even though they are classified as having a low risk due to the dams' technical characteristics, their conservation status and the dam safety plans (Resolution 143/2002 of the Brazilian Water Resources National Council). The avoidance of tailing production and the removal of tailing dams from the conservation unit may contribute to higher sustainability.

Additional sustainability may be achieved by increasing the amount of rehabilitated mine lands, although complete rehabilitation will be possible only after mine closure. Nevertheless, despite high operational efforts, the rehabilitation of particular mining environments remains challenging and requires research regarding the selection of native species adapted to environmental constraints and the development of soil management (Gastauer et al., 2018). Further compensation plantings are necessary to improve the CO_2 balance from mining operations.

Compared to our 2016 baseline, the energy efficiency and the percentage of reused water in the overall mining process declined. Both indicators depend on many factors, such as the amount of materials handled versus the amount of materials produced; the installation of new mines, which increases energy and water consumption without immediately contributing to higher iron ore production; climatic particularities, which vary from year to year (e.g., water use for dust suppression increases during drier years); and the development and installation of new energy- and water-efficient technologies. Therefore, longer periods should be analysed to identify the long-term trends of these indicators. Nevertheless, water and energy efficiency are key questions for the sustainability of mining operations, and the decline in the performance of both indicators should receive maximum attention from companies.

4.3. Data and methodological challenges for assessing sustainability indices

In the last two decades, an emergent sustainability science has been widely discussed in the scientific community (Kates et al., 2001; Parris and Kates, 2003; Shaker, 2018; Singh et al., 2012). Quantitative indices may also exhibit subjectivity; however, the advantage of using quantitative indices lies in their multidimensionality as well as the use of normalization and aggregation based on scientific rules and statistical methods (Singh et al., 2012). However, some limitations of this study should be highlighted. First, data were unavailable for many indicators of the physical environment proposed in studies on sustainability in mining sites around the world (Dialga, 2018; Marnika et al., 2015; Worral et al., 2009; Zvarivadza, 2018). Second, the evaluation conducted here is a snapshot of the *status quo* of Carajás iron ore mining operations, and we have ignored the fact that all iron mining activities within the CNF are highly dynamic (Nascimento et al., 2020); thus, modifications to some individual indicators, e.g., the increase in the percentage of revegetated mine land, are expected in the future. Third, the quantification of extraction relative to the lifetime of mines may be considered a premise of SD since future generations need to decide how they will or will not use iron ore in the future.

The selection of indicators and the normalization and aggregation method implied a value judgement. The aggregation method used (geometric mean) entails a partial non-constant compensability of the indicators. Most of the indicators used implied that noncompliance with some requirements can be compensated for by compliance with other requirements. Although the aggregation provides concise information that can be easily communicated to and followed by policy makers, analysing the performance of each indicator is also important. The five categories used have different numbers of indicators. Therefore, the calculation of the CESI using aggregation with equal weighting for the five categories results in a composite index equal to 2.62 due to the higher weighing for the indicators in the categories with fewer indicators (e.g., category 2). To analyse the impact of this choice, we also calculated the CESI using geometric aggregation of all indicators and without considering the five categories. Hence, the CESI under this method was smaller than that under the previous method (2.60).

Finally, the model presented here is based on a top-down methodology; all indicators and their threshold values were defined by academics, without consulting stakeholders from the corporate and operational divisions mining companies or the affected civil society. These stakeholders may have distinct perceptions of the importance and evaluation of individual indicators (Sonter et al., 2014). Therefore, this study should be complemented by a bottom-up methodology in which individual indicators and their categories are presented to stakeholders and civil society for evaluation. Based on such feedback, the importance of individual indicators may be weighted, allowing us to best meet the SDGs in mining (Sonesson et al., 2016).

Nowadays, the challenge is to develop comprehensive sustainability indices of mining encompassing multiple dimensions of sustainability. These dimensions must include environmental performance, including physical and biological aspects, organizational governance, economic and societal performance. When we develop indicators for measuring a baseline and performance monitoring, we will be able to establish a new paradigm to sustainability in mining. These indicators will be useful for both internal uses (e.g. mining companies), and for communication to external stakeholders (e.g. in the form of sustainability reports) (Singh et al., 2007). Furthermore, it is important to emphasize that more than one thousand mine closures over the past four decades in Australia. Laurence (2011) found that the economic and efficiency dimensions were causal factors in the 75% of mines that closed prematurely. Therefore, the big challenge is to assess the use of comprehensive economic and social indicators, anchored in the dimensions of sustainability, for remote areas, such as the Amazon.

5. Concluding remarks

Identifying individual indicators with low performance, the CESI of the physical mining environment of Carajás iron ore mining operations can indicate a path towards sustainability for the entire mining process in the region. Complemented by similar studies on sustainability regarding biodiversity and ecosystem services (i.e., the biotic environment) and socio-economic pillars, this study may improve the transformation of exploited natural capital into social and environmental capital that will improve the quality of life of people who work or live in mining townships. In this context, the values presented here represent baselines for further monitoring and evaluating the sustainability of the physical environment and allow the sustainability of iron ore exploitation in Carajás to be compared with further mining enterprises, guaranteeing mining operations with minimum environmental impacts in sensitive and specially protected areas.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank the Gerência de Meio Ambiente Ferrosos Norte, Gerência de Planejamento de Curto Prazo Carajás and the Gerência Executiva de Meio Ambiente of the Vale S.A. mining company for providing the information necessary for the quantification of some of the individual indicators presented here. Authors P.W.M.S.F and R.D would like to thank CNPq for research grant support, while D.C.S and G.N.S also thank CNPq for scholarships, and R.B.L.C is grateful to CAPES for the grants received for this research.

References

Araújo, E., Barreto, P., Baima, S., Gomes, M., 2017. Most deforested conservation units in the legal Amazon (2012 – 2015). IMAZON, Belém 92.

Arlidge, W.N.S., Bull, J.W., Addison, P.F.E., Burgass, M.J., Gianuca, D., Gorham, T.M., Jacob, C., Shumway, N., Sinclair, S.P., Watson, J.E.M., Wilcox, C., Milner-Gulland, E.J., 2018. A global mitigation hierarchy for nature conservation. BioScience 68, 336–347, 10.1093/biosci/biy029.

Azapagic, A., 2004. Developing a framework for sustainable development indicators for the mining and minerals industry. J. Clean. Prod. 12, 639–662. https://doi.org/10.1016/S0959-6526(03)00075-1.

Barber, C.P., Cochrane, M.A., Souza Jr., C.M., Laurance, W.F., 2014. Roads, deforestation, and the mitigating effect of protected areas in the Amazon. Biol. Conserv. 177, 203–209. https://doi.org/10.1016/j.biocon.2014.07.004.

Böhringer, C., Jochem, P.E.P., 2007. Measuring the immeasurable — a survey of sustainability indices. Ecol. Econ. 63, 1–8. https://doi.org/10.1016/j.ecolecon.2007.03.008.

Brancalion, P.H.S., Garcia, L.C., Loyola, R., Rodrigues, R.R., Pillar, V.D., Lewinsohn, T.M., 2016. A critical analysis of the Native Vegetation Protection Law of Brazil (2012): updates and ongoing initiatives. Natureza Conservação 14 (Suppl. 1), e1–e16. https://doi.org/10.1016/j.ncon.2016.03.004.

Brundtland, G.H., 1987. World Commission on Environment and Development. Our Common Future. Oxford University Press, Oxford.

Devecchi, M.F., Lovo, J., Moro, M.F., Andrino, C.O., Barbosa-Silva, R.G., Viana, P.L., Giulietti, A.M., Antar, G., Watanabe, M.T.C., Zappi, D.C., 2020. Beyond forests in the Amazon: biogeography and floristic relationships of the Amazonian savannas. Bot. J. Linn. Soc. 193 (4), 478–503, 10.1093/botlinnean/boaa025.

Dialga, I., 2018. A sustainability index of mining countries. J. Clean. Prod. 179, 278–291. https://doi.org/10.1016/j.jclepro.2017.12.185.

Dialga, I., 2019. A mining industry sustainability index: experiences from gold and uranium sectors. In: Muthu, S.S. (Ed.), Development and Quantification of Sustainability Indicators. Springer Singapore, Singapore, pp. 27–63. https://doi.org/10.1007/978-981-13-2556-4_2.

DNPM, 2017. Brazilian Mineral Yearbook – main metallic commodities. DNPM, Brasilia. http://www.anm.gov.br/dnpm/publicacoes/serie-estatisticas-e-economia-mineral/anuario-mineral/anuario-mineral-brasileiro/amb_metalicos2017.

Ebert, U., Welsch, H., 2004. Meaningful environmental indices: a social choice approach. J. Environ. Econ. Manag. 47, 270–283. https://doi.org/10.1016/j.jeem.2003.09.001.

Ellison, D., Morris, C.E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Noordwijk, M.v., Creed, I.F., Pokorny, J., Gaveau, D., Spracklen, D.V., Tobella, A.B., Ilstedt, U., Teuling, A.J., Gebrehiwot, S.G., Sands, D.C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., Sullivan, C.A., 2017. Trees, forests and water: cool insights for a hot world. Global Environ. Change 43, 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002.

Gastauer, M., Souza Filho, P.W.M., Ramos, S.J., Caldeira, C.F., Silva, J.R., Siqueira, J.O., Furtini Neto, A.E., 2018. Mine land rehabilitation in Brazil: goals and techniques in the context of legal requirements. Ambio. https://doi.org/10.1007/s13280-018-1053-8.

Gastauer, M., Trein, L., Schumacher, W., 2012. Enhancing biotic resource protection in Nettersheim: successful integration of forestry and agriculture in nature conservation concerns. Environ. Nat. Resour. Res. 2, 61–69, 10.5539/enrr.v2n4p61.

Gonçalves, A.R., 2016a. Plano de Manejo. Floresta Nacional de Carajás, vol. I. Brasília-DF, Brazil. Diagnóstivo. MMA/ICMBio.

Gonçalves, A.R., 2016b. Plano de Manejo. Floresta Nacional de Carajás, vol. II. MMA/ICMBio, Brasília-DF, Brazil. Planejamento.

Gorman, M.R., Dzombak, D.A., 2018. A review of sustainable mining and resource management: transitioning from the life cycle of the mine to the life cycle of the mineral. Resour. Conserv. Recycl. 137, 281–291. https://doi.org/10.1016/j.resconrec.2018.06.001.

Grainger, C.J., Groves, D.I., Tallarico, F.H.B., Fletcher, I.R., 2008. Metallogenesis of the Carajás mineral Province, southern Amazon craton, Brazil: varying styles of Archean through Paleoproterozoic to Neoproterozoic base- and precious-metal mineralisation. Ore Geol. Rev. 33, 451–489. https://doi.org/10.1016/j.oregeorev.2006.10.010.

GRI, G.R.I, 2013. Sustainability Reporting Guidelines. GRI, Boston,MA, p. 94.

Groombridge, B., 1992. Global Biodiversity: State of the Earth's Living Resources. Chapman and Hal, New York.

Hák, T., Janoušková, S., Moldan, B., 2016. Sustainable Development Goals: a need for relevant indicators. Ecol. Indicat. 60, 565–573. https://doi.org/10.1016/j.ecolind.2015.08.003.

ICMM, 2006. Good Practice Guidance for Mining and Biodiversity. International Council on Mining and Metals. ICMM, London, p. 142.

Jones, M., 2003. The concept of cultural landscape: discourse and narratives. In: Palang, H., Fry, G. (Eds.), Landscape Interfaces. Springer, Netherlands, pp. 21–51, 10.1007/978-94-017-0189-1_3.

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil quality: a concept, definition, and framework for evaluation (A guest editorial). Soil Sci. Soc. Am. J. 61, 4–10, 10.2136/sssaj1997.03615995006100010001x.

Kates, R.W., Clark, W.C., Corell, R., Hall, J.M., Jaeger, C.C., Lowe, I., McCarthy, J.J., Schellnhuber, H.J., Bolin, B., Dickson, N.M., Faucheux, S., Gallopin, G.C., Grübler, A., Huntley, B., Jäger, J., Jodha, N.S., Kasperson, R.E., Mabogunje, A., Matson, P., Mooney, H., Moore, B., Riordan, T., Svedin, U., 2001. Sustainability science. Science 292 (641), 10.1126/science.1059386.

Laurance, W.F., Goosem, M., Laurance, S.G.W., 2009. Impacts of roads and linear clearings on tropical forests. Trends Ecol. Evol. 24, 659–669. https://doi.org/10.1016/j.tree.2009.06.009.

Laurence, D., 2011. Establishing a sustainable mining operation: an overview. J. Clean. Prod. 19, 278–284. https://doi.org/10.1016/j.jclepro.2010.08.019.

Marnika, E., Christodoulou, E., Xenidis, A., 2015. Sustainable development indicators for mining sites in protected areas: tool development, ranking and scoring of potential environmental impacts and assessment of management scenarios. J. Clean. Prod. 101, 59–70. https://doi.org/10.1016/j.jclepro.2015.03.098.

Martins, F.D., Mendonça, M.V., 2014. Floresta Nacional de Carajás: compatibilizando a mineração com a preservação. In: Bensusan, N., Prates, A.P. (Eds.), A diversidade cabe na unidade?: áreas protegidas do Brasil. IEB, Brasília, pp. 580–591.

Meadows, D.H., 1972. Club of Rome. The Limits to Growth; a Report for the Club of Rome's Project on the Predicament of Mankind. Universe, New York.

Metzger, J.P., 2003. Effects of slash-and-burn fallow periods on landscape structure. Environ. Conserv. 30, 325–333. https://doi.org/10.1017/S0376892903000341.

Mota, J.A., Maneschy, M.C., Souza-Filho, P.W.M., Navarro-Torres, V.F., Siqueira, J.O., Santos, J.F., Matlaba, V., 2017. A new proposal for sustainability indicators in mining. Sustain. Debate 8, 15–29. https://doi.org/10.18472/SustDeb.v8n2.2017.21795.

Mudd, G.M., 2010. The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. Resour. Pol. 35, 98–115. https://doi.org/10.1016/j.resourpol.2009.12.001.

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., 2005. Tools for Composite Indicators Building. European Commission, Italy, p. 133.

Nascimento, F.S., Gastauer, M., Souza-Filho, P.W.M., Nascimento Jr., W.R., Santos, D.C., Costa, M.F., 2020. Land Cover Changes in Open-Cast Mining Complexes Based on High-Resolution Remote Sensing Data. Remote Sensing in press, 10.20944/preprints201908.0104.v1.

Parris, T.M., Kates, R.W., 2003. Characterizing and measuring sustainable development. Annu. Rev. Environ. Resour. 28, 559–586, 10.1146/annurev.energy.28.050302.105551.

Piló, L.B., Auler, A.S., Martins, F.D., 2015. Carajás national forest: iron ore plateaus and caves in southeastern Amazon. In: Vieira, B.C., Salgado, A.A.R., Santos, L.J.C. (Eds.), Landscapes and Landforms of Brazil. Springer, Berlin, pp. 273–283. https://doi.org/10.1007/978-94-017-8023-0_25.

Ricardo, F., Rolla, A., 2006. Mineração em Unidades de Conservação na Amazônia brasileira. Instituto Socioambiental, São Paulo.

Sahoo, P.K., Dall'Agnol, R., Salomão, G.N., da Silva Ferreira Junior, J., Silva, M.S., e Souza Filho, P.W.M., Powell, M.A., Angélica, R.S., Pontes, P.R., da Costa, M.F., Siqueira, J.O., 2019. High resolution hydrogeochemical survey and estimation of baseline concentrations of trace elements in surface water of the Itacaiúnas River Basin, southeastern Amazonia: implication for environmental studies. J. Geochem. Explor. https://doi.org/10.1016/j.gexplo.2019.06.003.

Sahoo, P.K., Dall'Agnol, R., Salomão, G.N., Junior, J.d.S.F., Silva, M.S., e Souza Filho, P.W.M., da Costa, M.L., Angélica, R.S., Filho, C.A.M., da Costa, M.F., Guilherme, L.R.G., Siqueira, J.O., 2020a. Regional-scale Mapping for Determining Geochemical Background Values in Soils of the Itacaiúnas River Basin, vol. 376. The use of compositional data analysis (CoDA), Brazil, p. 114504. https://doi.org/10.1016/j.geoderma.2020.114504. Geoderma.

Sahoo, P.K., Dall'Agnol, R., Salomão, G.N., da Silva Ferreira Junior, J., da Silva, M.S., Martins, G.C., e Souza Filho, P.W.M., Powell, M.A., Maurity, C.W., Angelica, R.S., da Costa, M.F., Siqueira, J.O., 2020b. Source and background threshold values of potentially toxic elements in soils by multivariate statistics and GIS-based mapping: a high density sampling survey in the Parauapebas basin, Brazilian Amazon. Environ. Geochem. Health 42, 255–282, 10.1007/s10653-019-00345-z.

Salomão, G.N., Dall'Agnol, R., Sahoo, P.K., Angélica, R.S., de Medeiros Filho, C.A., Ferreira Júnior, J.d.S., Sousa da Silva, M., Souza Filho, P.W.M.e., Nascimento Junior, W.d.R., da Costa, M.F., Guilherme, L.R.G., Siqueira, J.O.d., 2020. Geochemical mapping in stream sediments of the Carajás mineral Province: background values for the Itacaiúnas River watershed. Braz. Appl. Geochem. 118 (104608) https://doi.org/10.1016/j.apgeochem.2020.104608.

Salomão, G.N., Dall'Agnol, R., Sahoo, P.K., Ferreira Júnior, J.S., Silva, M.S., Souza-Filho, P.W.M., Berredo, J.F., Nascimento Jr., W.R., Costa, M.F., 2018. Geochemical distribution and thresholds values determination of heavy metals in stream water in the sub-basins of Vermelho and Sororó rivers. Itacaiúnas River watershed, Eastern Amazon. Brazil. Geochimica Brasiliensis 21, (in press). https://orcid.org/0000-0003-3729-7840.

Shaker, R.R., 2018. A mega-index for the Americas and its underlying sustainable development correlations. Ecol. Indicat. 89, 466–479. https://doi.org/10.1016/j.ecolind.2018.01.050.

Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2007. Development of composite sustainability performance index for steel industry. Ecol. Indicat. 7, 565–588. https://doi.org/10.1016/j.ecolind.2006.06.004.

Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2012. An overview of sustainability assessment methodologies. Ecol. Indicat. 15, 281–299. https://doi.org/10.1016/j.ecolind.2011.01.007.

Soares Filho, B.S., 2016. Role of Amazon Protected Areas, Especially the Conservation Units Supported by ARPA, in Reducing Deforestation. FUNBIO, Rio de Janeiro, p. 12.

Sonesson, C., Davidson, G., Sachs, L., 2016. Mapping mining to the sustainable development goals: an Atlas, p. 74. Geneva, Switzerland.

Sonter, L.J., Moran, C.J., Barrett, D.J., Soares-Filho, B.S., 2014. Processes of land use change in mining regions. J. Clean. Prod. 84, 494–501. https://doi.org/10.1016/j.jclepro.2014.03.084.

Souza-Filho, P., Nascimento, W., Santos, D., Weber, E., Silva, R., Siqueira, J., 2018. A GEOBIA approach for multitemporal land-cover and land-use change analysis in a tropical watershed in the southeastern Amazon. Rem. Sens. 10, 1–22, 10.3390/rs10111683.

Souza-Filho, P.W.M., de Souza, E.B., Silva Júnior, R.O., Nascimento Jr., W.R., Versiani de Mendonça, B.R., Guimarães, J.T.F., Dall'Agnol, R., Siqueira, J.O., 2016. Four decades of land-cover, land-use and hydroclimatology changes in the Itacaiúnas River watershed, southeastern Amazon. J. Environ. Manag. 167, 175–184. https://doi.org/10.1016/j.jenvman.2015.11.039.

Souza-Filho, P.W.M., Giannini, T.C., Jaffé, R., Giulietti, A.M., Santos, D.C., Nascimento Jr., W.R., Guimarães, J.T.F., Costa, M.F., Imperatriz- Fonseca, V.L., Siqueira, J.O., 2019. Mapping and quantification of ferruginous outcrop savannas in the Brazilian Amazon: a challenge for biodiversity conservation. PloS One 14 e0211095. 10.1371/journal.pone.0211095.

Svobodova, K., Sklenicka, P., Molnarova, K., Salek, M., 2012. Visual preferences for physical attributes of mining and post-mining landscapes with respect to the sociodemographic characteristics of respondents. Ecol. Eng. 43, 34–44. https://doi.org/10.1016/j.ecoleng.2011.08.007.

Tesfaw, A.T., Pfaff, A., Golden Kroner, R.E., Qin, S., Medeiros, R., Mascia, M.B., 2018. Land-use and land-cover change shape the sustainability and impacts of protected areas. Proc. Natl. Acad. Sci. Unit. States Am. https://doi.org/10.1073/pnas.1716462115.

Tolbert, G.E., Tremaine, J.W., Melcher, G.C., Gomes, C.B., 1971. The recently discovered Serra dos Carajas iron deposits, Northern Brazil. Econ. Geol. 66, 985–994. https://doi.org/10.2113/gsecongeo.66.7.985.

UN, 1982. A World Charter for Nature. United Nations, New York.

UN, 2012. Realizing The Future We Want for All. Report to the Secretary-General. UN System Task Team on the Post-2015 UN Development Agenda. United Nations, New York.

Worrall, R., Neil, D., Brereton, D., Mulligan, D., 2009. Towards a sustainability criteria and indicators framework for legacy mine land. J. Clean. Prod. 17, 1426–1434. https://doi.org/10.1016/j.jclepro.2009.04.013.

Zvarivadza, T., 2018. Sustainability in the mining industry: an evaluation of the National Planning Commission's diagnostic overview. Resour. Pol. https://doi.org/10.1016/j.resourpol.2018.01.008.