Proposal of an environmental sustainability index for open-pit mines using landscape fragmentation indicators

Proposta de um índice de sustentabilidade ambiental para minas a céu aberto com o uso de indicadores de fragmentação de paisagem

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Abstract

The perception of the environmental impacts caused by economic activities is subjective and usually negatively affects the image of an extractive sector such as mining. In order to avoid this, the environmental impact assessment must be supported by clear and well-selected environmental indicators. An index of sustainability was created to demonstrate that open-pit mining is comparable to other economic activities. The index is composed by of environmental indicators like water and energy consumption combined with an indicator of landscape fragmentation, using remote sensing data and geoprocessing. A comparative study considering a ten-year period was carried out with the biggest iron ore mine in Brazil, N5W, and the largest Brazilian soybean producer, the Sorriso County, in the Mato Grosso State to illustrate the methodology.

keywords: sustainability, open pit mining, environmental indicators.

Resumo

A percepção dos impactos ambientais das atividades econômicas pela sociedade é subjetiva e muitas vezes afeta negativamente a imagem de certos setores econômicos como a mineração. Para não ser subjetiva, a avaliação de impactos ambientais deve se embasar em indicadores ambientais claros e criteriosamente selecionados. Para demonstrar que a sustentabilidade da mineração a céu aberto é comparável a outras atividades econômicas, foi criado um índice de sustentabilidade ambiental composto do consumo de água e energia combinado com um indicador de fragmentação de paisagem construído com o uso de sensoriamento remoto e geoprocessamento. Para ilustrar a metodologia, foi realizado um estudo comparativo em um período de 10 anos entre a maior mina de minério de ferro brasileira, N5W, com o maior município produtor de soja, Sorriso, no Mato Grosso.

Palavras-chave: *sustentabilidade, mineração a céu aberto, indicadores ambientais.*

1. Introduction

After the publication of the Brundtland Report, which defines sustainable development as "Sustainable development is development that meets present needs without compromising the ability of future generations to meet their own needs" (BUTLIN, 1989), the issue of sustainability had spread and was incorporated into the traditional mindset. Although the concept of sustainability continues to evolve, the different methods of assessing the sustainability of economic activities has not yet converged on a common, standardized way and, therefore, distortions about the sustainability of economic activities continue to occur.

The open-pit mining is an economic activity capable of provoking significant environmental impacts. However, its environmental reputation is tarnished by a subjective perception of environmental sustainability. This fame is due not only to the bad practices of mining companies, but also to methodological errors. Mining is subject to applicable environmental compensation. This environmental compensation occurs due to strong environmental legislation that regulates the mining activity. Environmental compensations made primarily by large mining ventures soften the environmental performance of the activity. Other economic activities with a not so negative environmental image also cause significant environmental impacts. However, they are not seen as villains by the stakeholders. One example of these economic activities is agriculture, especially the cultivation of soybeans, due to the scale of magnitude of this culture in Brazil.

Therefore, it is necessary to use a methodology for assessment of environmental sustainability that can bring greater objectivity to the theme. The judicious selection of environmental indicators is critical to the assessment of environmental performance free of bias. Environmental indicators are quantifiable scientific information, easy to understand, used in decision-making processes at all levels of society, useful as tools for evaluation of intricate events, showing trends and progress that change over time. Environmental indicators allow for the simplification of information necessary to deal with a complex reality through the representation of a set of non-directly observable phenomena in a measure that illustrates and communicates the information that leads to a reduction of time and financial resources.

Environmental indicators are also seen as statistics that describe or summarize some aspects of the state of the environment, natural resources and related human activities (MMA, 2008). The great advantage of the use of indicators is to simplify the information about a complex reality (TAYRA E RIBEIRO, 2006). For example, the body temperature is an indicator of the state of health of homeothermic organisms: once known the temperature range related to the healthy state of the organism, temperature changes that are easily detectable by clinical thermometers are a good clue that something is wrong with the health. With only the temperature information, it is not possible to say with certainty what is wrong; one can only know that there is something wrong with the health of the individual.

Environmental indicators have the similar function in environmental sciences: to serve as a warning when the balance of the system is broken. Several authors agree that the characteristics of a good environmental indicator should include ease of interpretation, be originated from data widely available, have a scientific basis, be relevant to environmental policies and environmental management, and should be clear enough in communicating the results to the public (DRAMSTAD, 2009). A good indicator must also warn about a problem before it becomes too serious or irreparable. In addition, it is important that the indicator be amenable to quantification.

So three environmental indicators were chosen to evaluate the sustainability of mining and agriculture: the water and energy consumption and evaluation of landscape metrics for determining the fragmentation of the landscape caused by the activities. We chose these indicators because the water, and energy consumption contribute to various direct and indirect environmental impacts (TEIXEIRA, 2005; GOLDEMBERG E LUCON, 2007; BERNARDO, 2008). The water and energy consumption are related to the type of activity and the production process. Therefore, there will be limits on their reductions. The measure of reducing water and energy consumption is correlated with the commitment of the company (or producers, in the case of agriculture) with the environment. Moreover, these two indicators have a high correlation with many other environmental indicators and can be used as their substitutes.

About indicators of landscape fragmentation, the surface of the Earth is subject to constant changes in its shape, which is the result of a myriad of natural and anthropogenic disturbances. The disturbances caused by human activities may take a variety of forms, such as deforestation, destruction of habitats, growth of urban areas, all of them increasing the fragmentation of natural landscapes. An enormous amount of ecosystems have been converted to pasture, plantations, mining and many other ventures. All these activities contribute to the satisfaction of the basic needs of society (BOTEQUILHA LEITÃO, 2006). Changes in the natural landscape resulting from a variety of human activities cause severe environmental impacts in the natural environment as habitat losses that undermine the continuity of entire populations and ecological communities (FAHRIG, 2007).

An effective environmental monitoring of large areas is through remote sensing, geoprocessing and use of GIS (geographic information systems). The remote sensing contributes to environmental monitoring through the speed and frequency of primary data provided by the satellites; the geoprocessing is essential in the treatment of the data, and the GIS facilitate the management of spatial information supporting decision-making (JACINTHO, 2003).

An index of environmental performance was created to assess the sustainability of the two economic activities compared in this study, in which each indicator received a weight between 0 and 1. A difficult question to answer is related to the choice and the significance of each indicator for the local environment. There is not an answer that applies to all cases. In a place where there is scarcity of water, as a desert region, the water consumption can be more meaningful than the landscape fragmentation. On the other hand, in a place of great importance to the maintenance of biodiversity or of rare beauty, the importance of these two indicators might be different. The weights of each indicator in the index of sustainability still generate debate in the scientific community. One of the advantages of weights, however, is the ability to assign new values to them when new environmental factors become significant, or when other environmental boundary conditions or legal restrictions arise. There are many methodologies used to define the importance of each indicator in the sustainability index. MUSEE AND LORENZEN (2007) used the Fuzzy logic in his assessment of the sustainability of a gold mine. SINGER *et al.* (2012) chose a space multicriteria decision analysis based on GIS and analytic hierarchical process to calculate the weights of each bookmark in the environmental performance index. In this study, we use Saaty's methodology -the analytic hierarchy process- to calculate the weight of each indicator (SAATY, 1980). The weights of each indicator were varied to find out weights values that make the environmental performance index score equivalent to both economic activities.

2. Material and methods

Study Areas

This study is focused on two areas in Brazil. The mining area is the Carajas Complex, where the mine selected for the study is located, N5W, and it belongs to Vale Mining Company. The Carajas Complex is in the Parauapebas County. The Parauapebas County belongs to the State of Pará, located in the northern region of Brazil. The largest soybean producer is located in Sorriso County in the Mato Grosso State, Brazil. The Sorriso County was selected to represent the economic activity of soybean farming due to the difficulty in identifying the producers alone. The selection of these two areas of research is justified for some reasons. First, both have a single economic activity, which facilitates the satellite data classification. Second, the production of both areas has a similar order of magnitude (millions of tons of grain or ore per year). Finally, both study areas are located in northern Brazil, within the limits of the Legal Amazon, sharing various climatological characteristics among themselves as shown in Figure 1.

Study Areas Location

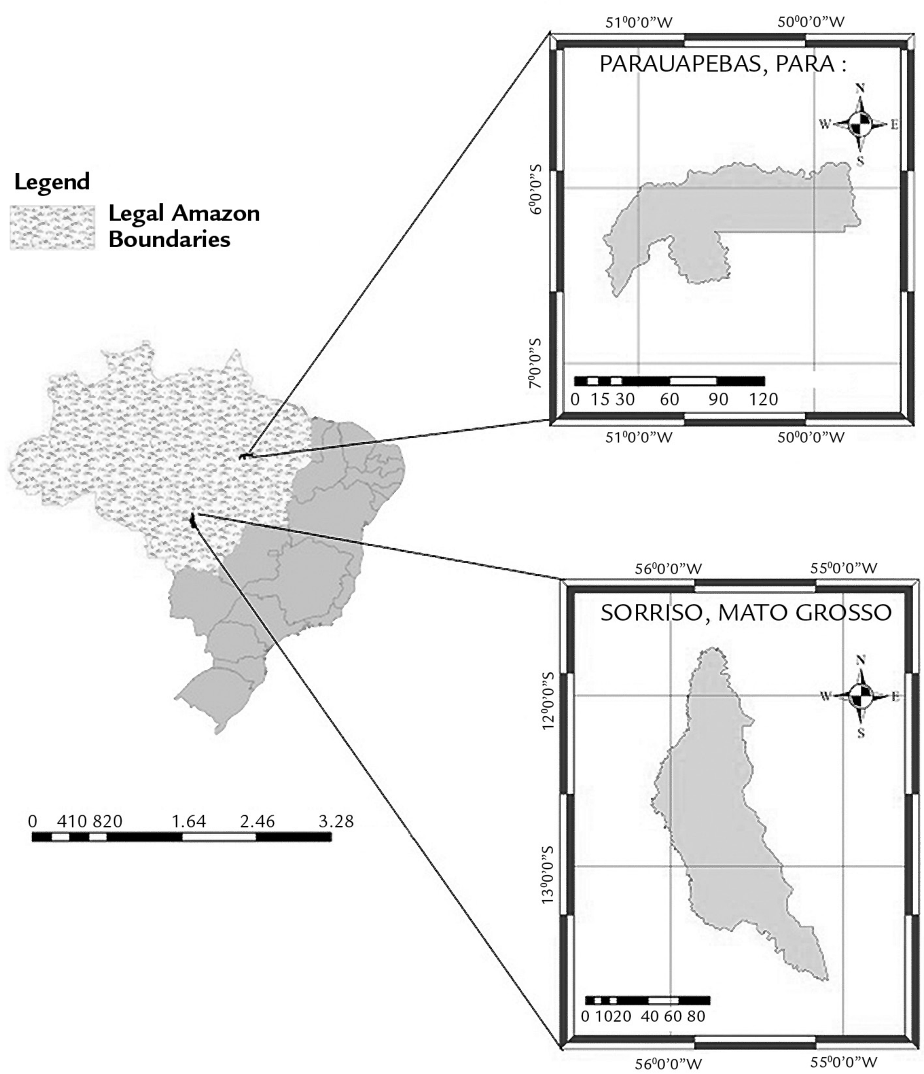


Figure 1
Study areas location.

The climate of both locations is continental equatorial climate throughout most of the year. The rains are plentiful, with an annual average of 1,500 mm to 1,700 mm and can exceed 3,000 mm in Parauapebas. The rainy season lasts about six months. The annual average temperature range lies between 240 c to 270 c, being classified as low thermal amplitude, with a slight cooling in the winter, which is characteristic of hot and humid climate. Parauapebas has 153,908 inhabitants according to the Census of 2010 and is the sixth-largest County in the Pará State with 6,886.2 km2 of the total area. Parauapebas has an average elevation of 140 m. Sorriso has 66,521 inhabitants according to the Census of 2010 (IBGE, 2013) and has 9,329.6 km2 of area. The County is considered to be the national capital of agribusiness and the world largest producer of soybean.

The average altitude of Sorriso is 365 m. Both counties had large forested areas before the beginning of its economic activities.

Environmental Indicators

In this study, three environmental indicators were evaluated: energy consumption, water consumption and fragmentation of the landscape. The indicators were selected based on the following principles:

(i) play an important role in the degradation of environmental conditions;

(ii) be measurable;

(iii) having data available or easy to obtain, and

(iv) there was no significant correlation between them. The energy and water consumption and water data were obtained from two sources. First, the N5W mine data were published in Vale's Sustainability Report (VALE, 2010), and the soybean culture data were obtained from statistics of the Ministry of Agriculture of Brazil for the years 2000 and 2010. A life cycle assessment of soybean culture [16] was used in estimating the consumption of water and energy of a soybean crop because these data depend on many factors, such as soil type, local rain regime, local climate (CAVALETT, 2008); Therefore, it is difficult to quantify. Tables 1 and 2 summarize the results.

Sorriso – MT - Brazil

Cropped Area (ha)	Production (ton)	Productivity (ton/ha)	Water Consumption (m^3)	Energy Consumption (kWh)
618,182	1,700,000	2.75	3,338,182	1,292,000

N5W Mine- PA - Brazil

Mined area (ha)	Production (ton)	Productivity (ton/ha)	Water Consumption (m^3)	Energy Consumption (kWh)
500	36,000,000	72,000	23,292,840	19,800,000

Table 1
Environmental Indicators - Year 2000.

Sorriso – MT - Brazil

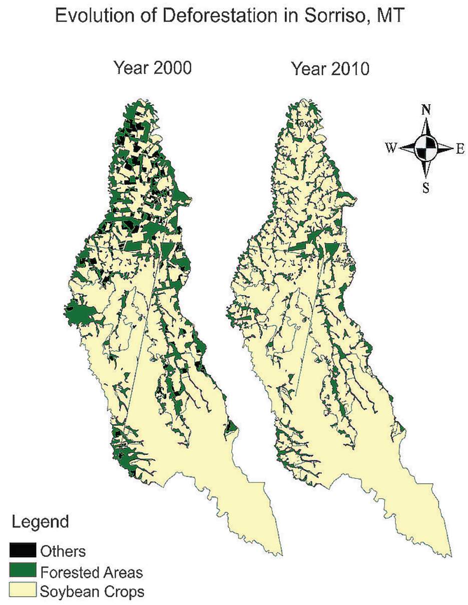
Cropped Area (ha)	Production (ton)	Productivity (ton/ha)	Water Consumption (m^3)	Energy Consumption (kWh)
875,851	2,903,446	3.315	4,729,595	1,830,529

N5W Mine- PA - Brazil

Mined area (ha)	Production (ton)	Productivity (ton/ha)	Water Consumption (m^3)	Energy Consumption (kWh)
500	49,000,000	98,000	31,704,143	26,950,000

Table 2
Environmental Indicators - Year 2010.

The satellite images which were used in this study were generated by the remote sensor of the Landsat 5 Thematic Mapper satellite. Once acquired, the images were radiometrically corrected, to hold the composition of the images. After the composition, the satellite images were georeferenced in SIRGAS 2000 datum and imported into the geoprocessing software. Then they were joined into a mosaic because the Sorriso County has taken more of a scene from the Landsat 5 satellite. The scenes were then clipped using the geoprocessing tool called Clip using as limit the boundaries of the Sorriso County. The images had to be classified as supervised classification technique so they could be used in FRAGSTATS software that calculates landscape fragmentation (McGARIGAL, CUSHMAN AND ENE, 2012). Figure 2 shows the classified satellite images which were used in this work for the cultivation of soybeans and mined areas.



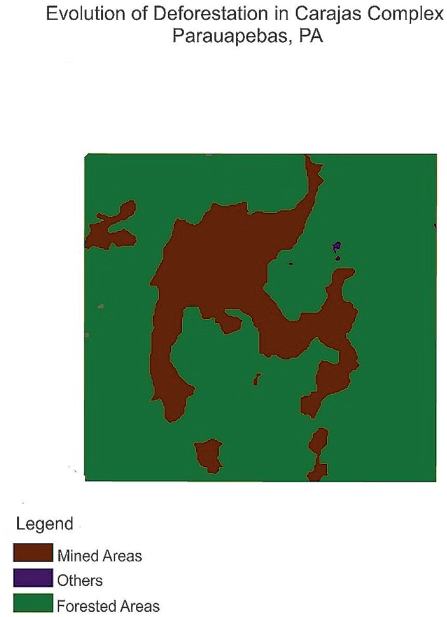


Figure 2
Study areas in years
2000 and 2010 classified
by geoprocessing software.

Regarding the N5W mine, only one image is shown because there was no significant increase in landscape fragmentation over ten years that were detectable during the period by the spatial resolution of Landsat (30 m x30 m per pixel). Fragmentation of the landscape was evaluated with the Fragstats software in a landscape level. The PlanD metric, which calculates the percentage of deforested area in comparison with the total landscape, was used for the purposes of evaluation of deforested areas by both the soy culture and mining. The forested areas fragmented and isolated from each other were also quantified. The values of each indicator were normalized because the environmental indicators are typically measured in different units, and their absolute values are very different [18]. According to DIAS-BALTEIRO AND ROMERO (2004), standardization when the indicator is of type "the smaller is the better" is given by equation 1:

$$\overline{I} = 1 - \frac{I_j - I_j^*}{I_{*j} - I_j^*}, \forall\, i, j \qquad (1)$$

where $\overline{I}$ is the standardized indicator, I_j is the indicator score, I_j^* is the smallest score of each indicator and e I_{*j} is the worst score measured for the j-est indicator. After the three environmental indicators have been normalized, the weight of each one of them was calculated through the AHP method (analytical hierarchy process or analytic hierarchical process). Finally, a standardized sustainability indicator (SSI) was calculated using Equation 2:

$$SSI = \sum_{i=1}^{n} w_i\, i \qquad (2)$$

Where wi is the weight of environmental indicator i, i is the environmental indicator standardized and n is the number of variables. The higher the value of the SSI, the worse is the environmental performance of economic activity. It was decided to assign to the fragmentation of the landscape a considerable relevance (in this case, 5, on a scale of 1 to 9). The fragmentation of the landscape is the main indicator in comparison with the other two indicators. The reason for this is the importance of forests in Brazil in the areas of study for harboring a large number of species which means possess high biodiversity and therefore have priority importance to the environment in the case of Brazil.

Energy consumption has received score 1 to represent the relevance of this indicator in the index (on a 1 to 10 scale), and water consumption has received score 3.

The reason for these scores is the importance of these indicators for Brazilian Environment. Energy consumption has received score 1 because 44.8% of energy generated is from renewable sources in Brazil. Water consumption has received score 3 because Brazil has abundant water resources. For this reason, the water consumption for the Brazilian case acquires a minor significance in comparison with countries with water shortage, as the desert countries. The weights were then calculated with the method AHP (analytic hierarchy process). Table 3 presents the results of applying the AHP.

Weights		
Energy Consumption	0.20	
Water Consumption	0.7	
Landscape Fragmentation	0.3	
Landscape fragmentation		
	Deforested area 2000 (ha)	Deforested area 2010 (ha)
Sorriso - MT	740,674	809,.332
N5W - PA	4,407	4,576
	Standardized Deforested area 2000	Standardized Deforested area 2010
Sorriso - MT	0.458	0.513
N5W - PA	0.348	0.437

Table 3
Indicators weights derived from AHP Methodology and landscape fragmentation data.

3. Results

Both economic activities expanded during the period analyzed as can be observed from the data of water and energy consumption. In relation to the cultivation of soybeans, in the period between 2000 and 2010 in Sorriso the land used for soybeans crops had a growth of 41.8%, which led to 82% reduction in forested areas and an increase of 45% in water consumption and 34% in energy consumption. In the year 2000, soybeans crops accounted for 66% of the total area of the county while in 2010 accounted for 94%. The N5W mine in the studied period also increased its production of iron ore and, therefore, the consumption of water and power increased as well. The water and energy consumption increased 36% during the period considered. However, the area used for mining had no significant increase detectable by the spatial resolution of the sensor TM of Landsat 5 satellite, which can be attributed to the expansion of mining in areas previously affected. The landscape fragmentation is much more intense in the activity of the soybean crop since in 2000 the deforested area was 740,674 hectares and accounted for 79.3% of the total area of the Sorriso county. In 2010, the deforestation advanced to 809,332 hectares equivalent to 86.7% of Sorriso. These values were expected for agriculture because this activity takes up vast expanses of soil. The landscape fragmentation reached levels so high that only the reduction of cultivated areas could improve the environmental performance of the soybean crop. However, the mining does not cause much impact on landscape fragmentation due to two factors: the advancement of mining that occurs in depth and the preservation of protected areas by legal requirement. The environment performance of both economic activities is shown in Figure 3.

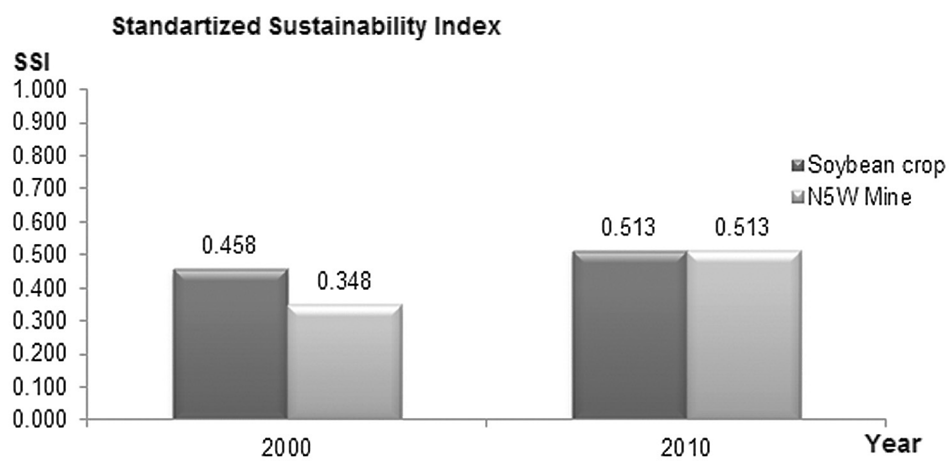


Figure 3
Environmental performance of the economic activities.

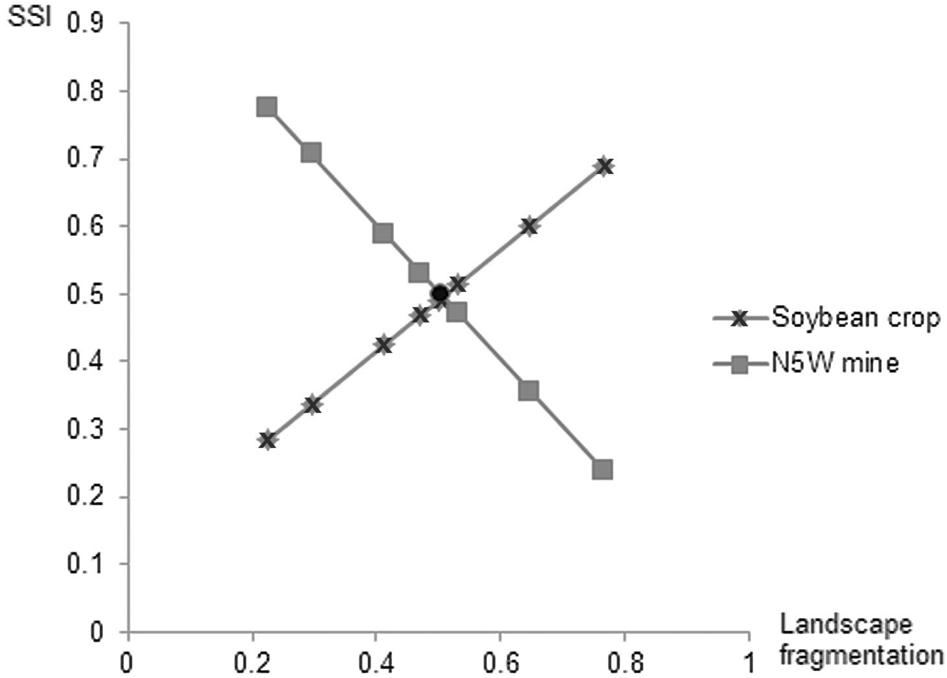


Figure 4
SSI variation as a function of landscape fragmentation indicator weight.

This value is significant because it shows the minimum weight to be assigned to the landscape fragmentation indicator in order to maintain the environmental competitiveness of mining, which can guide future mining projects in the search for a better environmental sustainability. By assigning an importance greater than 0.5 for the fragmentation of the landscape, open-pit mining becomes competitive in terms of sustainability in comparison with other economic activities.

4. Conclusions

The importance of iron ore mining and soybean crop is crucial for society because both supply basic human need activities to such an extent that their absence would endanger the existence of modern society. Different requirements on the part of environmental legislation and supervision of environmental agencies shape the environmental performance of economic activities. Agriculture is arguably an economic activity which is economically and environmentally unsustainable, if environmental externalities of economic activity are assumed by the farmers. The massive investments made by the large mining companies in search of better environmental performance makes mining an activity that even though it causes significant environmental impacts has its environmental impacts arising from the use of the soil largely decreased by the compensatory measures. The annual sustainability report published by Vale shows that 77% of the 4.7 million m³ of water are recycled within the mining plant. The energy consumed in the mine N5W comes from the energy matrix composed of 20% of renewable energy and 80% of non-renewable energy. The investments in research and development aim to reduce by 10% the use of non-renewable sources of energy until 2020. The National Forest of Carajás is a federal conservation unit located in the South of Pará State. It is managed by the Chico Mendes Institute for Biodiversity Conservation (ICMBio). The National Forest of Carajás had 412,000 hectares and was created by Federal Decree 2,486/98. The mineral exploitation is allowed within the protected area, and the mining company Vale has the right to use. If the company had not contributed to protecting the area, even though the reasons are historically strategic, probably landscape fragmentation on site would hit much larger levels, comparable to the local neighborhood not adopted by the company. Initiatives by the Brazilian environmental protection agencies to impose harsh conditions to environmental licensing of mining created a culture among the miners of continuous improvement of its environmental performance. On the other hand, weak legal, environmental standards and the widespread perception that agriculture causes minor environmental impacts for being a green activity brought a serious threat to the integrity of the Brazilian natural landscape.All information used in the article were obtained from public sources. The study presented is not intended to promote economic activity to the detriment of another, but present a sustainability assessment methodology that can provide the comparison of sustainability of economic activities, balancing environmental factors symbolized by the indicators.

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